Extreme Particle Accelerators

Felix Aharonian

CDY joint seminar, 02.06.2021

Extreme Acceleratoras ?

all phenomena in the Universe are extreme …

Topic - a research area - part of High Energy astrophysics/Astroparticle Physics

Does “extreme” imply something special ? Yes

Not too narrow? No

Motivation: machines operating on the edge of reality

incredibly high (close to 100 %) efficiency of

(1) conversion of the available energy to nonthermal particles

(2) acceleration rate of individual particles

evidence of their existence:

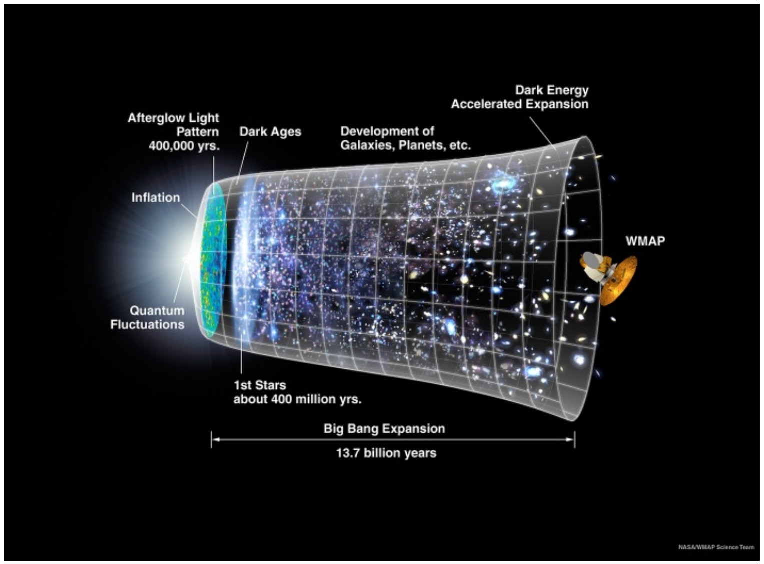
10^{20} eV CRs, Crab Flares, LHAASO PeVatrons…

Physics - ED/MHD/SR… Astrophysics - from pulsars to AGN

Objective: Physics and Astrophysics of these (perfectly designed) machines

can be done combining efforts and expertise of researchers from different disciplines and research areas, both theorists & observers

Universe as an extreme and high energy phenomenon



in the framework of "Big Bang Theory"

- the "Universe" is a high energy phenomenon
- its birth was an incredibly energetic event
- quite a long time it was "hot soup" consisting of relativistic particles and radiation ($E > m_e c^2$)

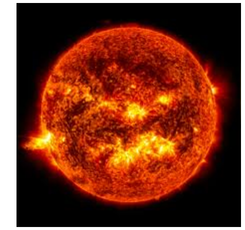
2.7 K MBR ($\sim 10^{-3}$ eV) is the remnant of that "soup"

now it is cold but contains Cosmic Ray Factories - particle accelerators producing the 4th substance - after matter, radiation and magnetic fields - of the visible Universe

Relativistic Nonthermal Plasma ("Cosmic Rays")

except for principal questions "why&how" the Universe perhaps is a simpler object than Extreme Cosmic Ray Factories operating on the edge of reality

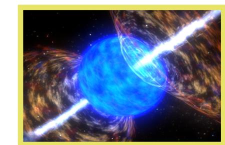
Relativistic Matter Factories

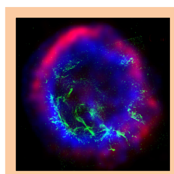


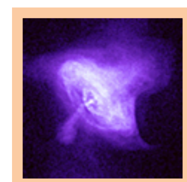
nonthermal processes in Universe proceed everywhere and on all astronomical scales:

Neutron Stars/Pulsars 

Black Holes 

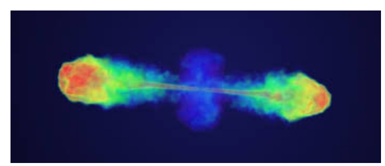
γ-ray Bursts 

Supernova Remnants 

Pulsar Wind Nebulae 

Massive Stars 

Starburst Galaxies 

AGN Jets 

GalaxyClusters 

High Energy Astrophysics

major objective: study of ***nonthermal*** phenomena in

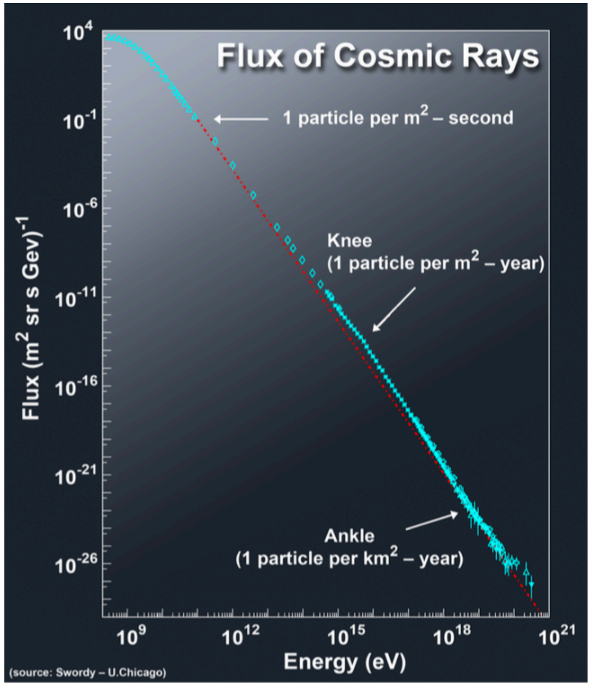
most energetic and violent forms in the Universe

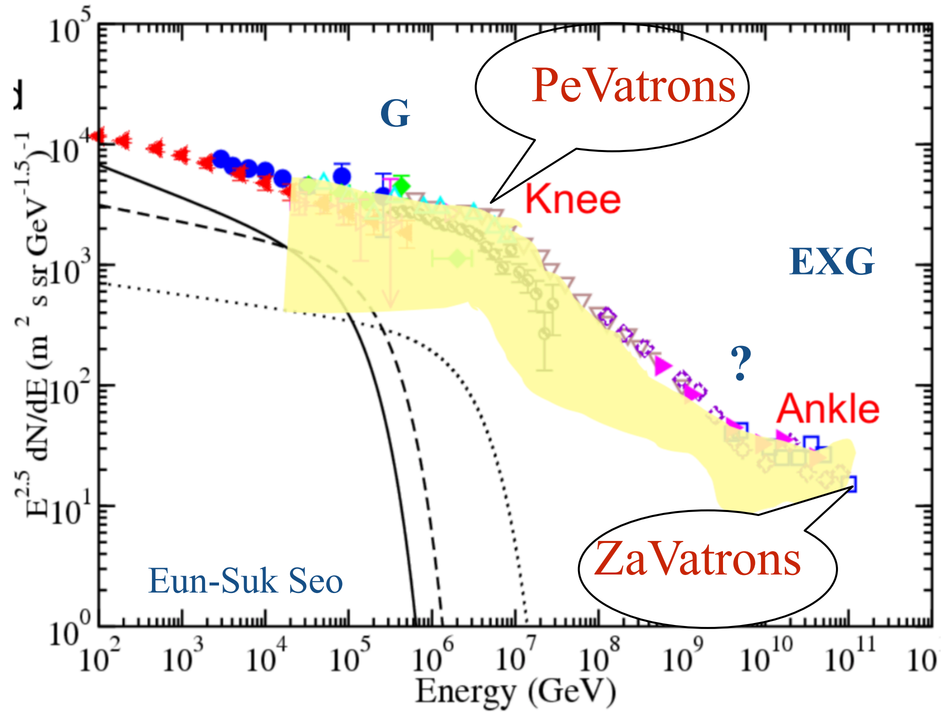
many research topics are related, in one way or another, to exploration of Nature's perfectly designed machines:

Extreme Particle Accelerators

“Origin of cosmic rays remains a mystery…”

a standard statement used in reviews/textbooks over many decades





below 10^{15} eV - G challenge : > 10^{15} eV

topmost challenge

beyond 10^{18} eV - EXG. challenge: > 10^{20} eV

between 10^{15}-10^{18} eV transition ???

PeVatrons and ZeVatrons - extreme accelerators what does mean "Origin of Cosmic Rays" ?

term "Cosmic Rays" itself has two meanings:

- locally detected nonthermal/relativistic particles - a "local fog"
- the "4th substance" of the visible Universe (after the matter, radiation and magnetic fields) - a *more fundamental issue*

Origin of CRs generally is reduced to the identification of the major contributors (SNRs, pulsars, GC, etc.) to the 'local fog'

this issue principally cannot be addressed by observations of charged CRs

CR factories can be identified only by neutral stable messengers: photons and neutrinos (also neutrons with $E>10^{14}(d/1pc)$ eV)

recent gamma-ray discoveries - a breakthrough in the field

hundreds of GeV and/or TeV gamma-ray emitters have been discovered representing 10+ source populations:

- SNRs, Stellar Clusters, GMCs
- Pulsars, PWNe
- Binaries (Binary Pulsars, Microquasars)
- Galaxies, Starburst Galaxies
- Clusters of Galaxies
- Radiogalaxies,
- AGN,
- GRBs

analogy with thermal X-rays:
as cosmic plasmas are easily heated up to keV temperatures - almost everywhere, particles (electrons and protons/nuclei) can be easily accelerated to TeV/PeV energies - almost everywhere!

not all of them contribute to local CR flux but all are Particle Accelerators - factories of relativistic matter

questions beyond the origin of local CRs: the physics of Extreme Accelerators

machines where acceleration proceeds with efficiency close to 100%

(i) fraction of available energy converted to nonthermal particles

in PWNe and perhaps also in SNRs *can be as large as 50 %*

(ii) maximum possible energy achieved by individual particles

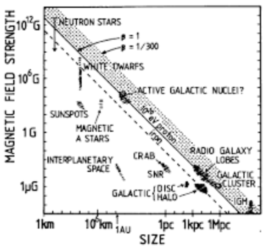
acceleration rate close to the *maximum (theoretically) possible rate*

acceleration rate: $\dot{E} = e\mathcal{E}c = \eta eBc; \quad \eta = \mathcal{E}/B \leq 1$

$\eta = 1$ - absolute extreme accelerator determined by ED and ideal MHD combined with the Synchrotron energy lose rate

Crab Nebula and Sources of of 10^{20} eV Cosmic Rays are Absolute Extreme Accelerators

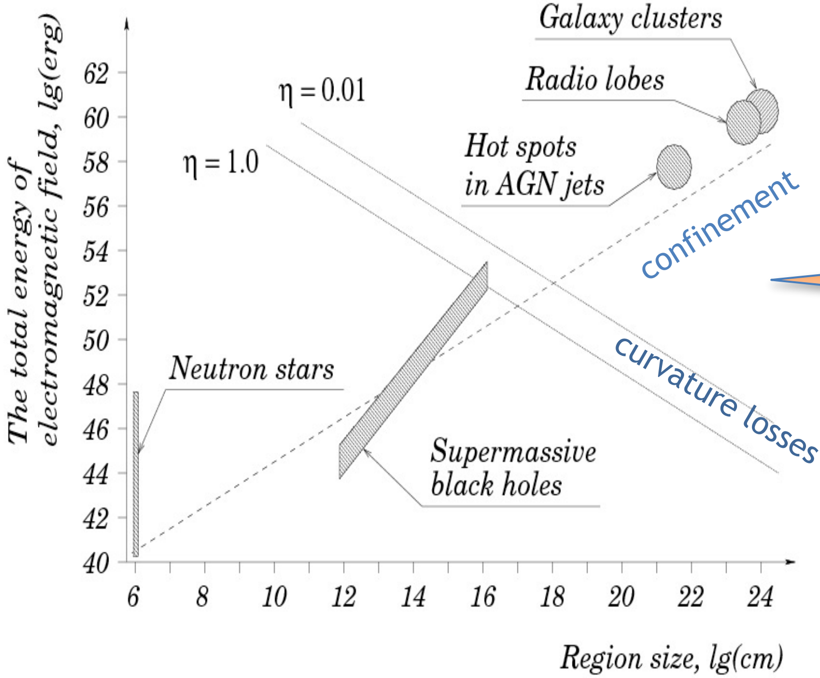
1984

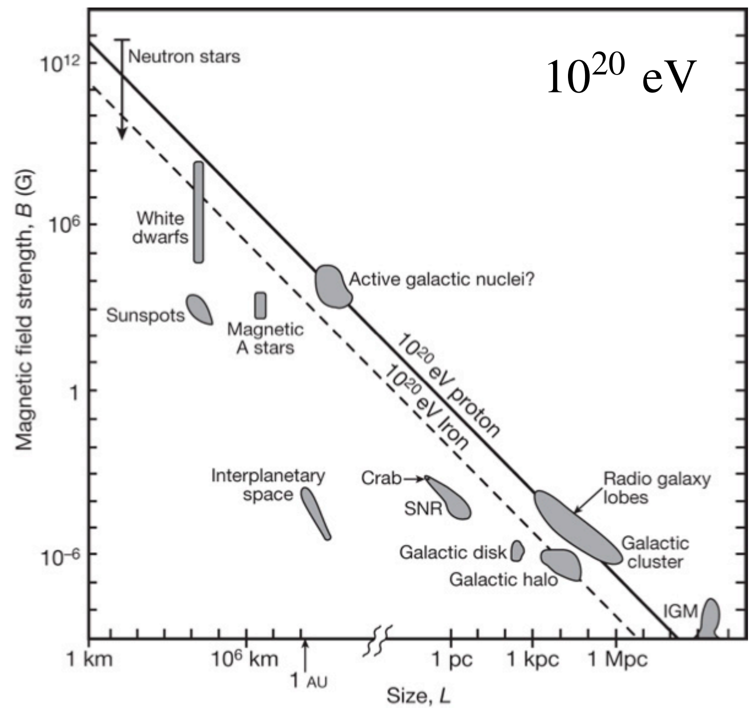


“Hillas plot” : $R_L \leq R$ $E_{20} \leq 10 R_{pc} B_G$

trivial and non-trivial implications

“Clearly, very few sites remain as possibilities: either one wants highly condensed objects with huge B or enormously extended object”





more conventional (synchrotron) losses: $E_{20} \leq 2\eta^{1/2} B_G^{-1/2}$

B-field in “10^{20}eV factories” cannot exceed 1 G;

unless is moving with bulk motion Lorentz factor $\Gamma \leq 30$, $B \leq 1$ kG

acceleration sites of 10^{20} eV CRs ?

$$t_{\rm acc} = \frac{R_L}{c}\eta^{-1}$$

signatures of extreme accelerators?

✓ synchrotron self-regulated cutoff:

$$h\nu_{\rm cut} = \frac{9}{4}\alpha_f^{-1} mc^2 \eta :$$

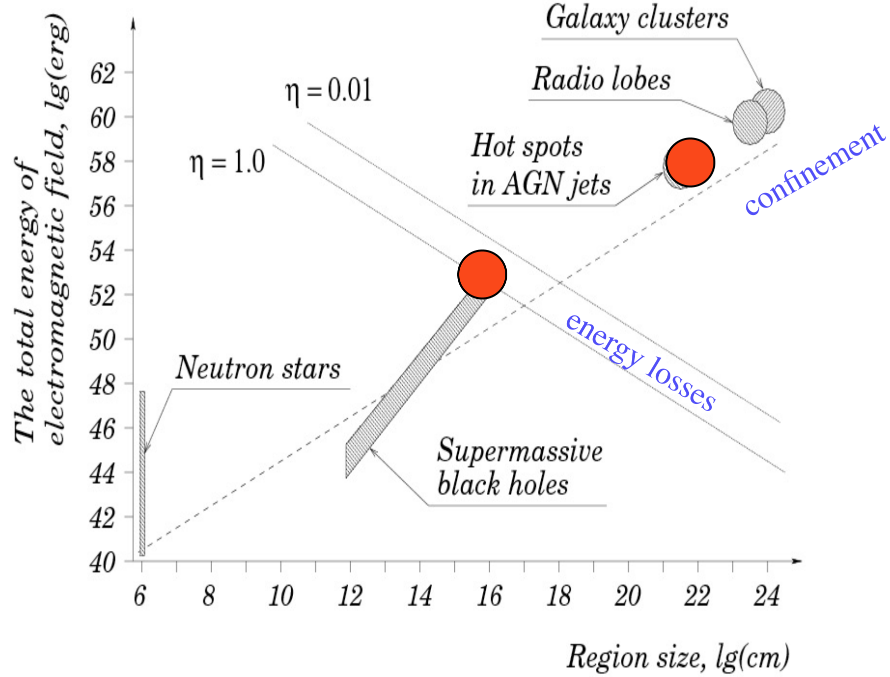
$\simeq$ 300GeV proton synchrotron
$\simeq$ 150MeV electron synchrotron

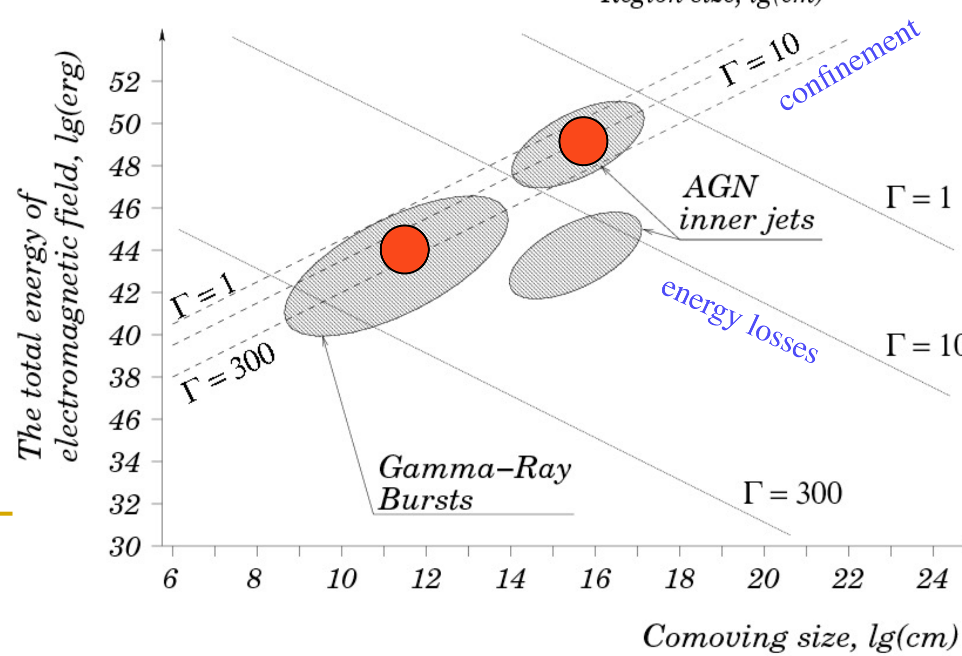
a viable "hadronic" model applicable for TeV γ-ray blazars if B ~ 100 G or so

✓ neutrinos (through "converter" mechanism) production of neutrons (through pγ interactions) which travel without losses and at large distances convert again to protons => Γ^2 energy gain!

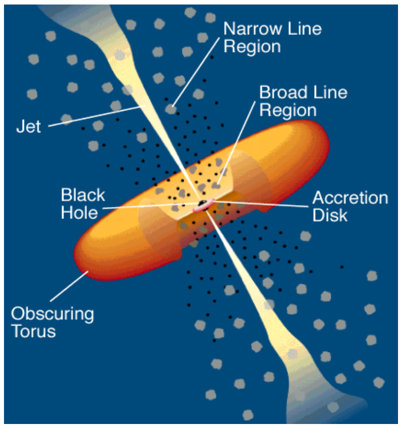
✓ observable off-axis radiation
radiation pattern can be much broader than 1/Γ

*) in nonrelativistic shocks $\eta \approx 0.1(v_{\rm shock}/c)^2$





Blazars - sub-class of AGN dominated by nonthermal/variable broad band (from R to γ) radiation produced in relativistic jets close to the line of sight, with massive Black Holes as central engines



GeV/TeV gamma-ray observations

strong impact on

- Blazar physics and astrophysics
- Diffuse Extragalactic Background (EBL)
  Intergalactic Magnetic fields (IGMF)

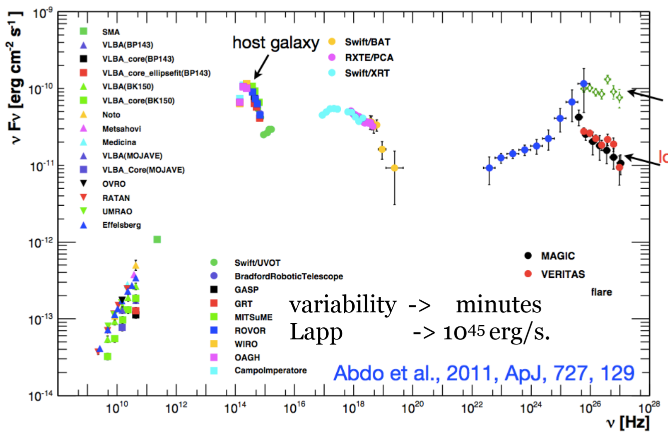
most exciting results of recent years

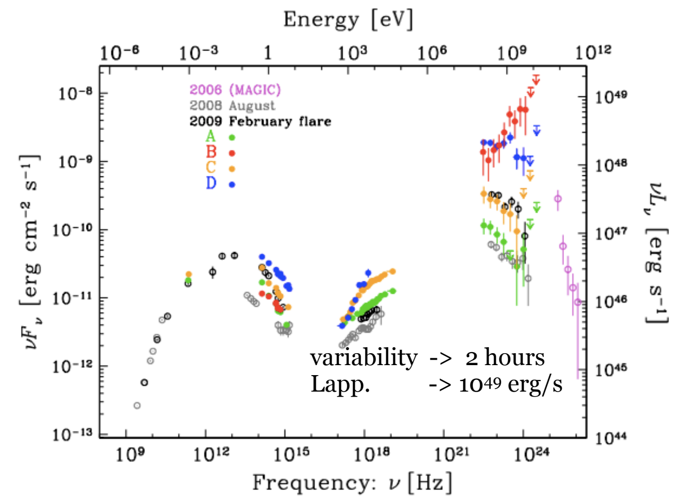
- ultra short time variability (on min scales)
- Jet power exceeds Eddington luminosity
- extremely hard (harder than E-1.5) energy spectra
- VHE blazars up to z~1!

Blazars - inefficient acccelerators or extreme accelerators?

a typical GeB blazar: 3C 279

a typical TeV blazar: Mkn 501





"standard" SSC or IC model for gamma-rays

if this is the case - nothing to do with EHE CRs - too small B-field (B < 1 G)

synchrotron cutoff at IR (GeV blazars) and X-ray (TeV blazers) => $\eta \sim (h\nu/100\ \mathrm{MeV})^{-1}\ \Gamma^{-1} \lll 1$

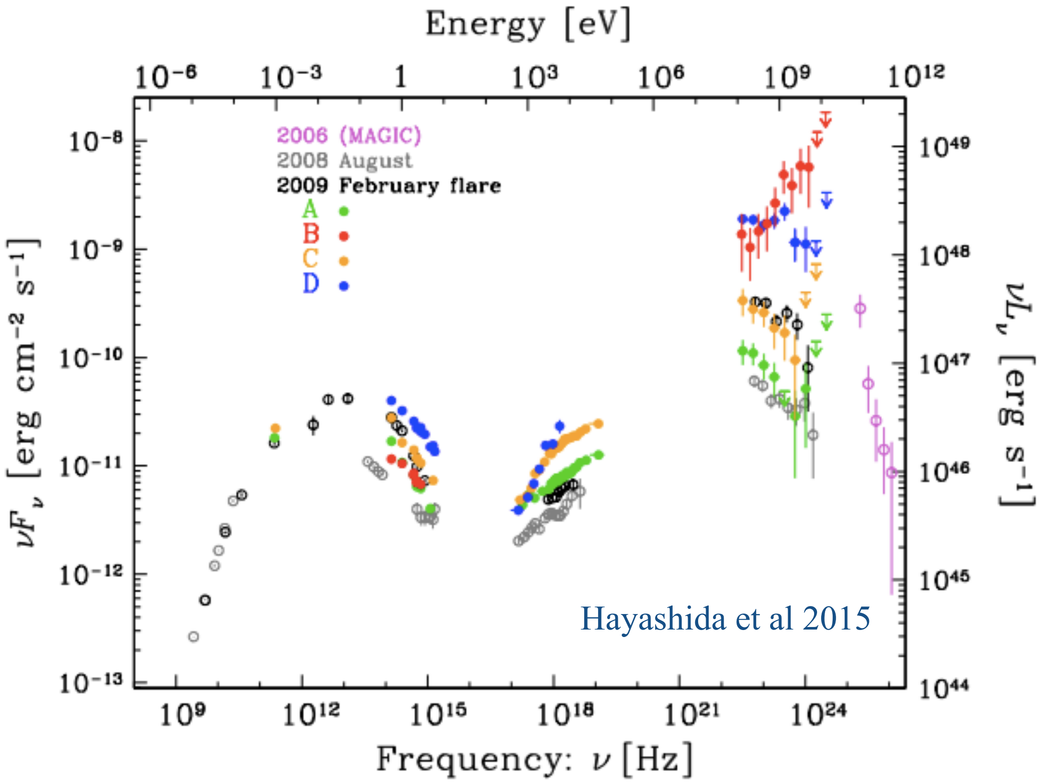
independent of the EHE CR related issue, B << 1 G and η << 1 is a big problem

hadronic models in synchrotron-loss dominated regime

$$\mathrm{E_{p,max}} = 3/2(\mathrm{e}^3\mathrm{B}\eta)^{-1/2}\mathrm{m_p^2 c^4} \approx 1.8\times 10^{19}\mathrm{B}_{100}^{-1/2}\eta^{-1/2}\mathrm{eV}$$

for $\mathrm{L} \le 10^{-3}\mathrm{pc}$ B should be as large as 300G => $\mathrm{E_{p,max}} \approx 10^{19}$ eV

bulk motion Lorentz factor exceeding Γ=10 is needed !



2013-14 flares of 3C 273:

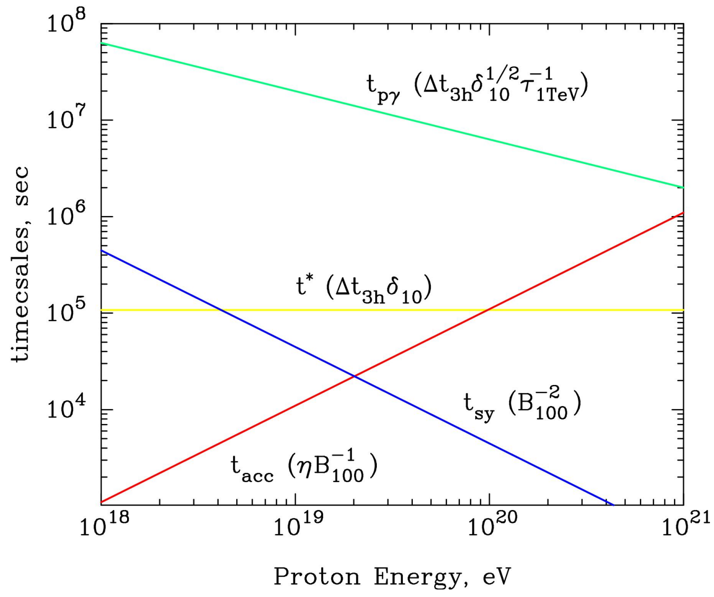
$\Delta t \sim 2$ hours
Lapp $\sim 10^{49}$ erg/s
unusually hard spectra

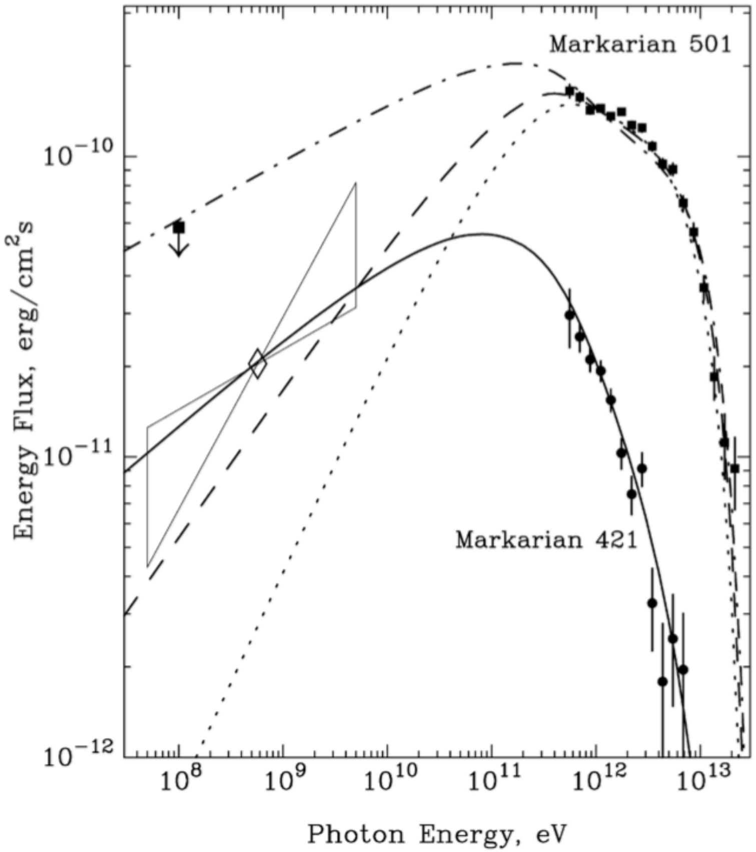
"leptonic versus hadronic" - of course it's important to clarify

but now we face more serious challenges (for all models):

1. ultrafast variability ~ Rg/c
2. jet power > Eddington luminosity

Synchrotron radiation of an extreme proton accelerator





E_{cut}=90 (B/100G)(Ep/10^{19} eV)^2 GeV

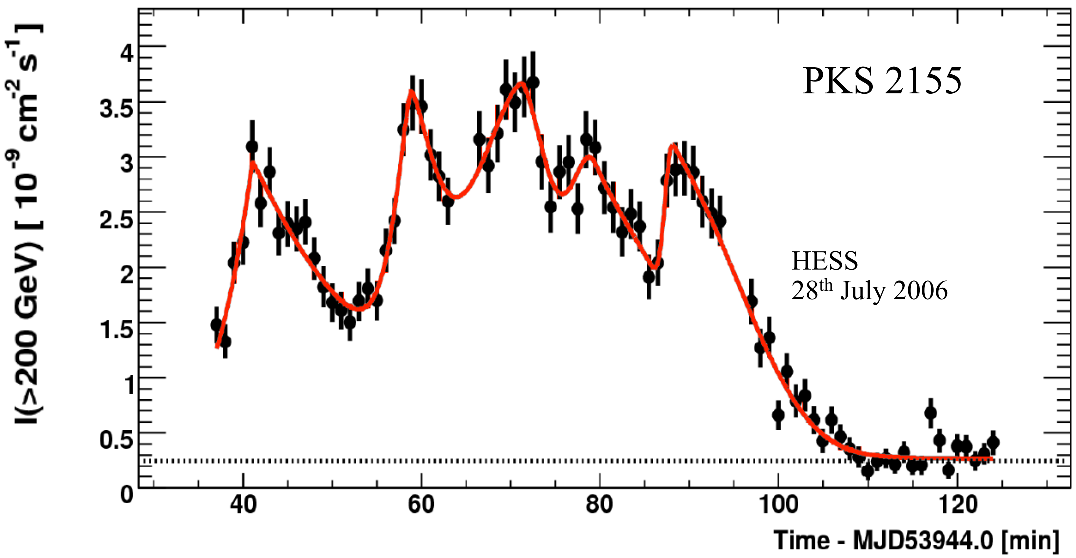
t_{synch}=4.5x10^4(B/100G)$^{-2}$ (E/10^{19} eV)$^{-1}$ s

t_{acc}=1.1x10^4 (E/10^{19}) (B/100G)$^{-1}$ s

cooling time of pγ interactions >> synchrotron cooling time => negligible neutrons flux

FA 2000

Light curve of PKS 2155-304 during 2006 July flare
variability timescale $\Delta t\sim$ 3 min: L< $c\Delta t\sim 6\ 10^{12}$cm!



it is convenient to express the variability through

$$\Delta t = R_g/c \sim 10\ (M/10^8 M_o)\ \text{min}$$

$R_g = GM_{BH}/c^2 = 1.5\ 10^{13} M_8$ cm is gravitation radius of Kerr BH

how the ultrafast ("sub-horizon") flares can be explained?

1. γ-rays are produced in (parts of) BH magnetospheres?

   perhaps in M87, but certainly not for distant blazers

2. obviously one needs yo invoke relativistic effects, and the perturbations in the jets responsible for flares should have external origin (not directly linked to central black hole)

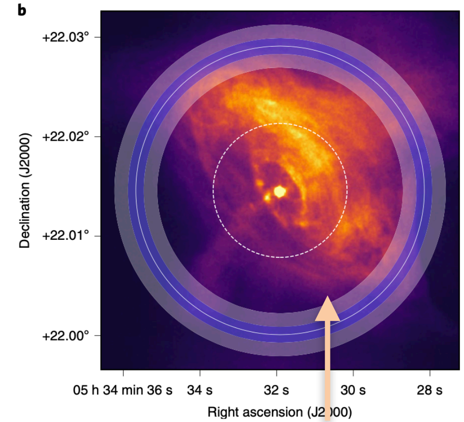
   two possibilities are under discussion:

   - "jet in jet"

   - "star - jet interactions"

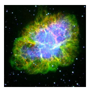
Crab pulsar/wind/nebula: *Absolute Extreme Accelerator*

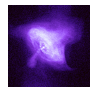
Chandra



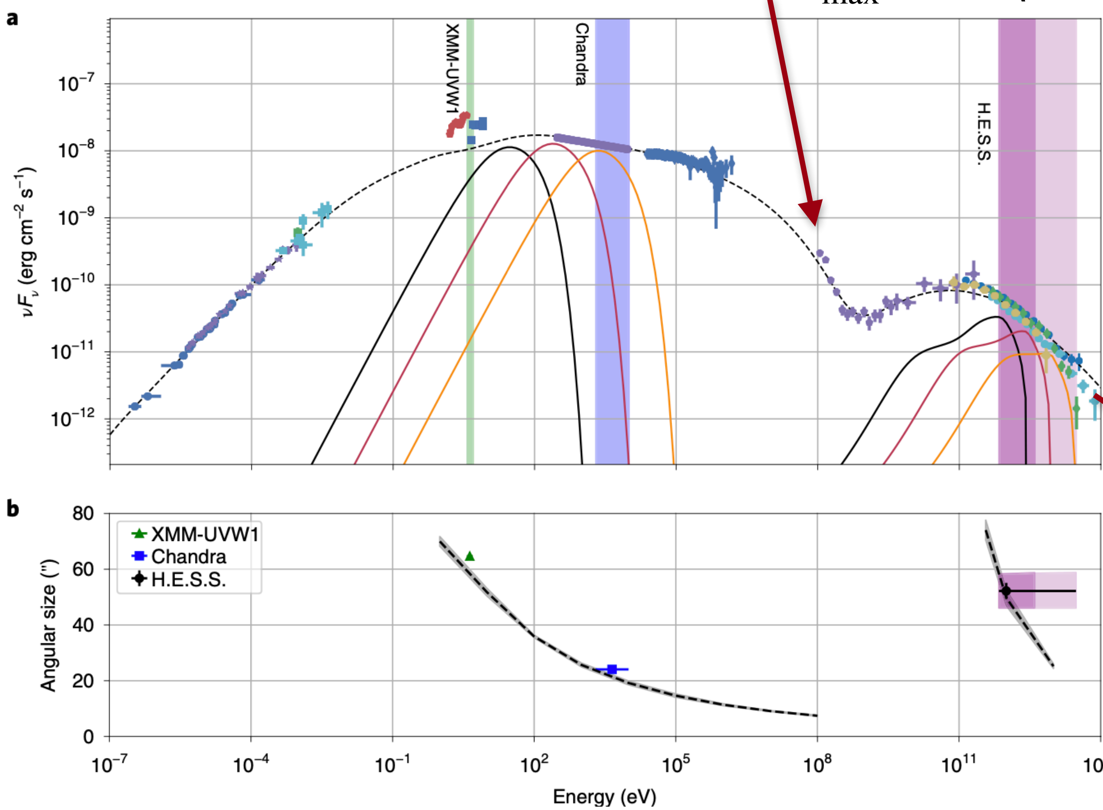
HESS

- conversion of the rotational energy of pulsar to non-thermal energy with efficiency ~50 %
- electron acceleration with 100 % efficiency





$h\nu_{max} \sim 100\eta$ MeV



1 PeV

LHAASO

max energy electrons:

$$E_{max} \approx 6\eta^{-1/2}(B/100\mu G)^{-1/2}$$

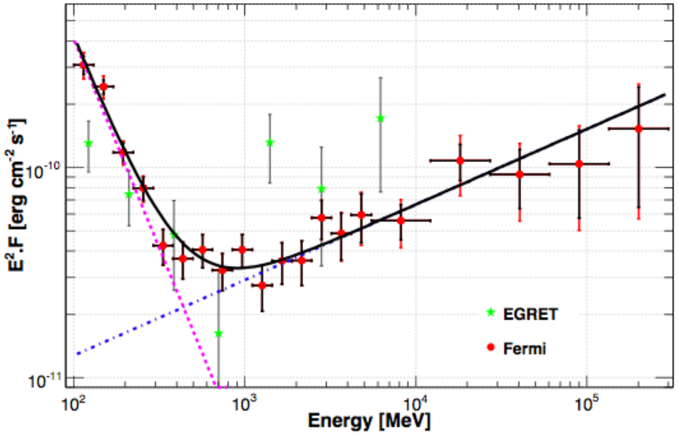
$$E_\gamma \approx 0.37(E_e/1\ \text{PeV})^{1.3}\ \text{PeV}$$

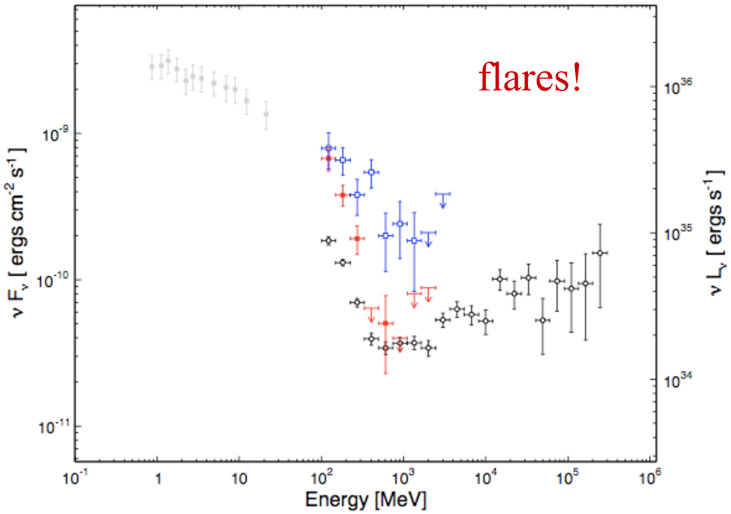
$$\eta = E/B \leq 1$$

$\eta = 1$ extreme accelerator !

$$h\nu \approx 9.3(E_\gamma/1\ \text{PeV})^{1.5}(B/100\mu G)\ \text{MeV}$$

Flares of Crab (Nebula) :





IC emission consistent with average nebular B-field: B ~ 100μG-150μG

seems to be in agreements with the standard PWN picture, but … MeV/GeV flares!!

although the reported flares perhaps can be explained within the standard picture - no simple answers to several principal questions - extension to GeV energies, B>1mG, etc.

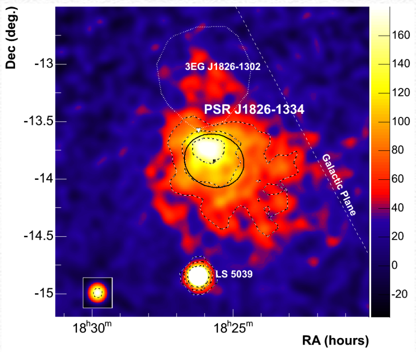
<u>observations of 100TeV gamma-rays</u> - IC photons produced by electrons responsible for synchrotron flares - a key towards understanding of the nature of MeV/GeV flares

efficiency of gamma-ray production

Crab is effective electron accelerator but not effective gamma-ray emitter

because of $B \geq 100\mu G, \;\; \kappa \sim 10^{-3}$

other ("standard") PWNe are effective accelerators/effective gamma-ray emitters



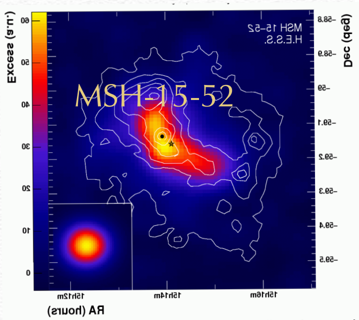
$$t \geq t_{cool}, \;\; \kappa = t_{Sy}/t_{IC} \approx 1(B/3\mu G)^{-2}$$

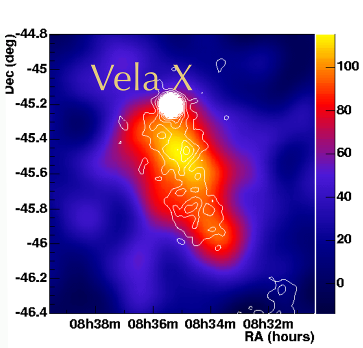
compensates smaller spin-down luminosities of "standard" PWNe

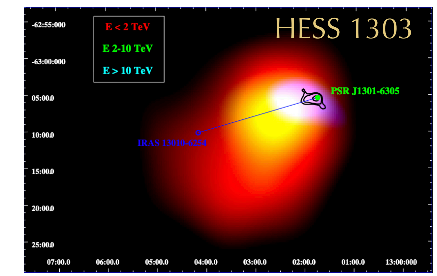
robust (assumption-free!) derivation of spatial and energy distribution of multi-TeV electrons absolutely unique in astrophysics; great for development of models, theories, concepts

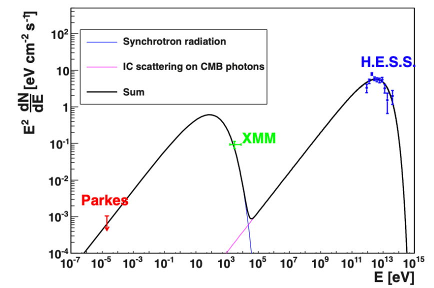
HESS standard PWNe:

or PWNe (MHD structure) + Pulsar Halos (IC of electrons after they escape PWN)



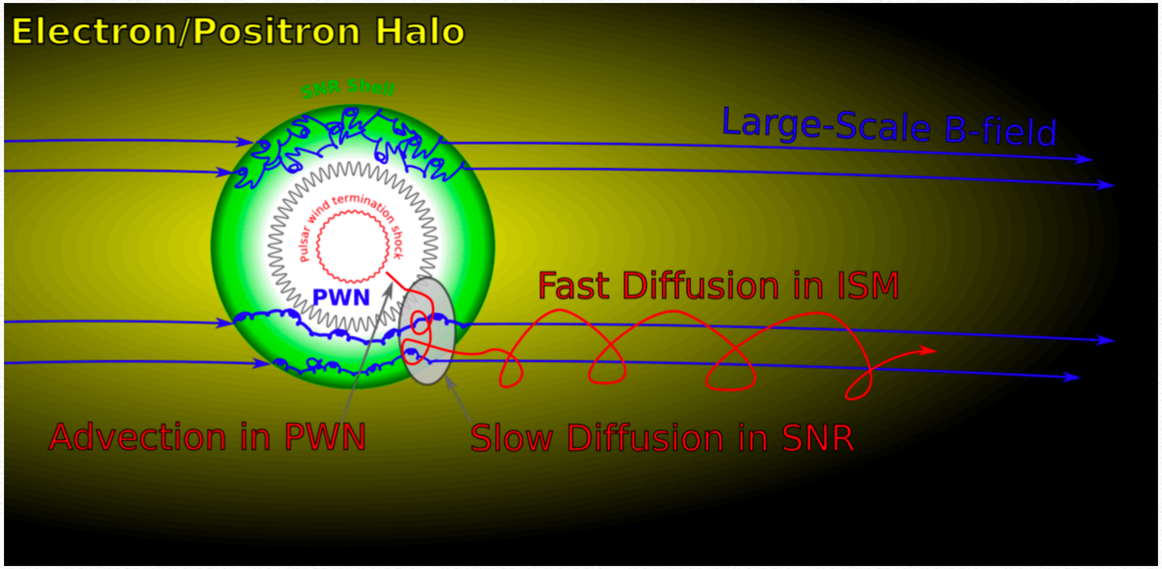






Energy dependent morphology

very low B-field $B \sim 1.4\mu G$



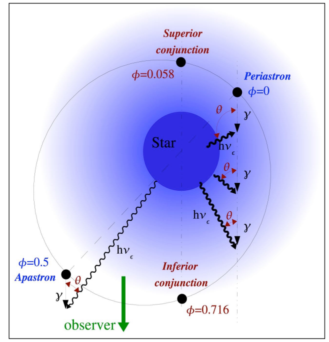
PWNe - MHD structure

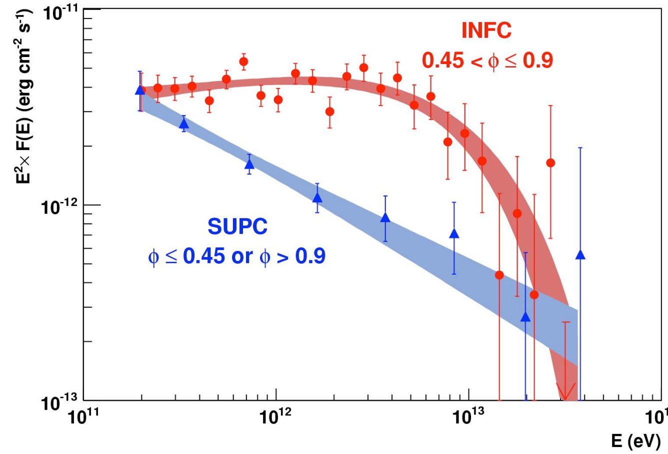
PHs - diffusively expanding cloud of electrons

LS 5039

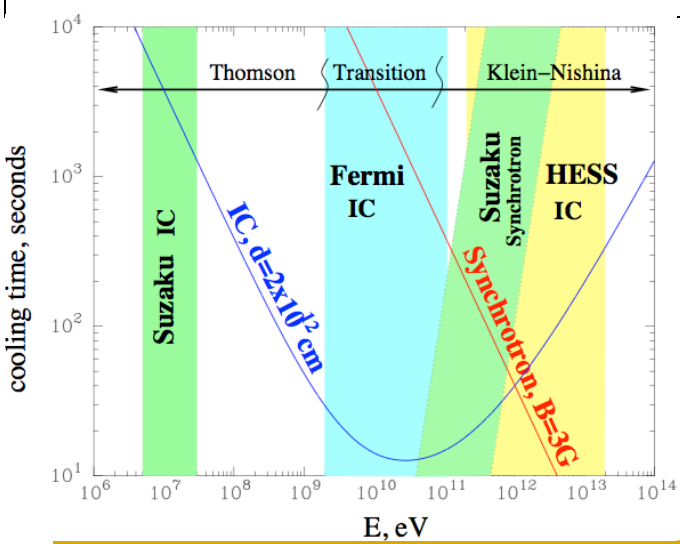
works as a perfect TeV clock
and an extreme accelerator

close to inferior conjuction - maximum
close to superior conjuction – minimum





modulation of the gamma-ray signal? *a quite natural reason (because of γ−γ absorption), but we see a different picture… anisotropic IC scattering? yes, but perhaps some additional factors (adiabatic losses, modest Doppler boosting) also play a non-negligible role*



can electrons be accelerated to energies up to 20 TeV in presence of dense radiation? *yes, but accelerator should not be located deep inside binary system; even at the edge of the system η < 10 => although* the origin of the compact object is not yet known (pulsar or a BH) and we do not understand many details, it is clear that this binary system works as an extreme accelerator

Galactic Cosmic Rays

Cosmic Rays: primary component + secondary component

primary: directly accelerated p, A, e^-, e^+

secondary: A, γ , ν, e^+, $\bar{p}$ produced in interactions of primary CRs with ISM

secondary/primary fraction X => "grammage" Λ
=> confinement time T => diffusion coefficient $D(E) \propto E^{\delta}$

source - injection spectrum into ISM $S(E) \propto E^{-\alpha}$

CR spectrum in ISM - modulated $\Phi(E) \propto E^{-\Gamma}; \; \Gamma = \alpha + \delta$

Galactic Cosmic Rays: sources ?

SNRs as prime candidates - over decades the conviction has been based on phenomenological arguments and theoretical meditations

- as early as 1933 W. Baade and Zwicky recognized the comparable energetics characterizing SN explosions and CRs and envisaged a link between

  $E_{SN} \sim 10^{51}$ erg, $R \sim 0.03$ yr $^{-1}$, $P_{SN} \sim 10^{42}$ erg/s => 10 % to CRs ?

- Diffusive Shock Acceleration theory applied to SNRs - viable mechanism for acceleration of particles with hard E^{-2} type spectrum in young (< 3 kyr) SNRs up to 1 PeV ? Difficult but in principle possible - amplification of the magnetic field in upstream is a critical issue

- direct prove - gamma-rays, neutrinos

Probing SNRs with gamma-rays

SNRs as the most likely sources

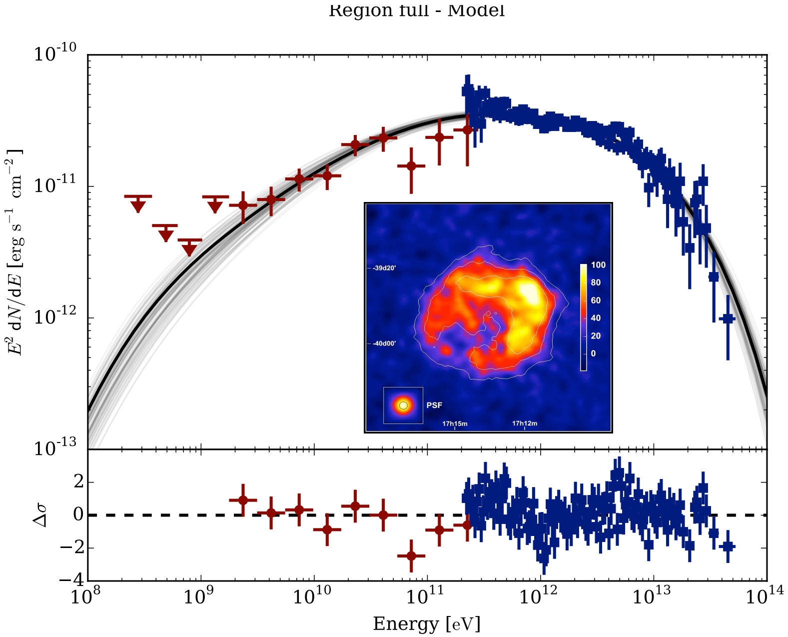
of galactic cosmic rays up to 1 PeV?

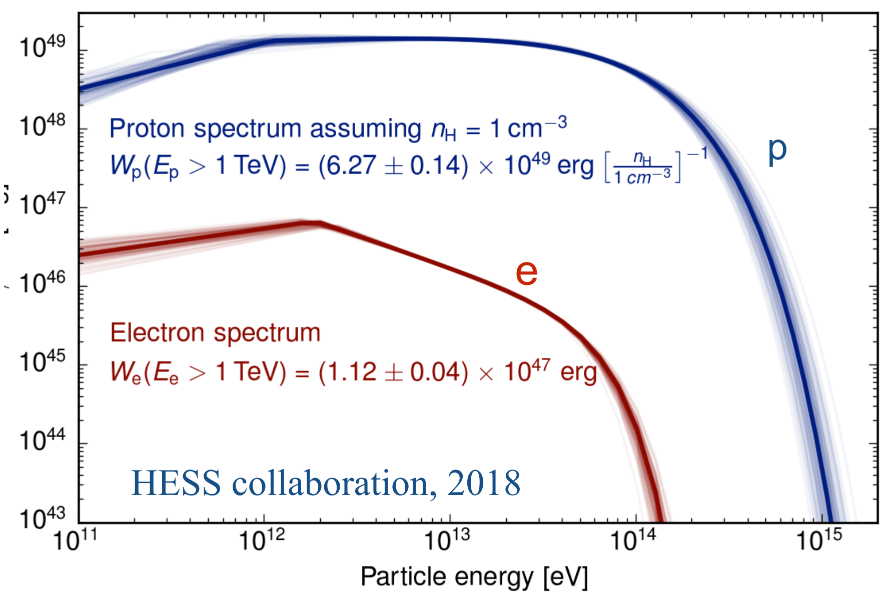
main hope is related to gamma-ray observations:

- detect VHE gamma-rays from SNRs
- demonstrate that they have hadronic origin
- demonstrate that proton spectra continue up to 1 PeV

Probing the distributions of accelerated particles in SNRs

Fermi+HESS measurements **RXJ 1713** derived spectra of e and p

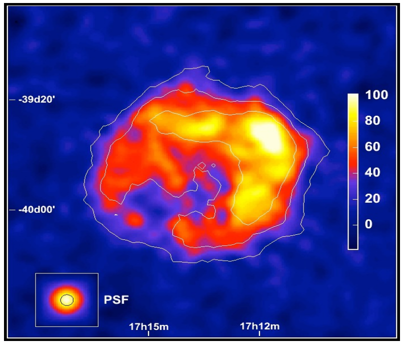




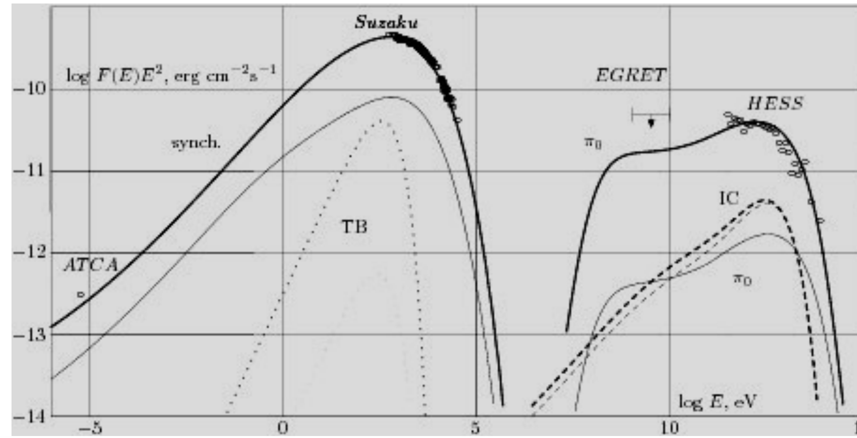
cutoff /break in the proton spectrum at 100 TeV

RXJ 1713.7-4639

modeling of broad-band SEDs:

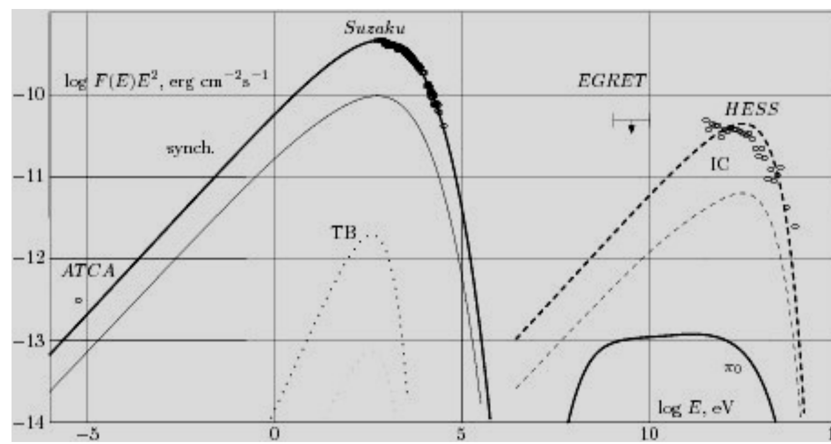


hadronic model



good spectral fit, reasonable radial profile, but …
(1) lack of thermal emission - possible explanation?
>70% energy is released in acceleration of protons!
(2) very high p/e ratio (10^4)

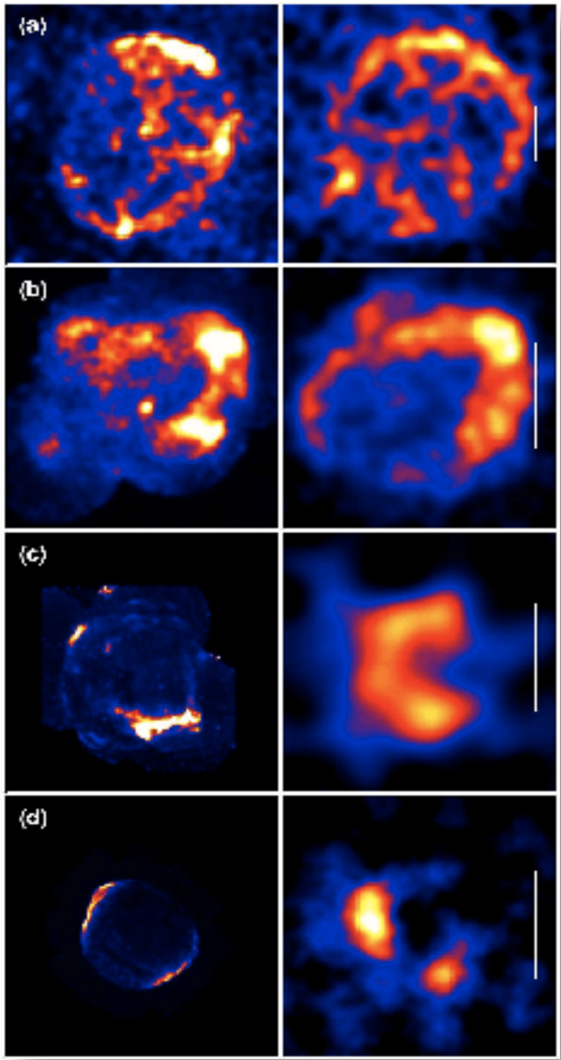
leptonic model



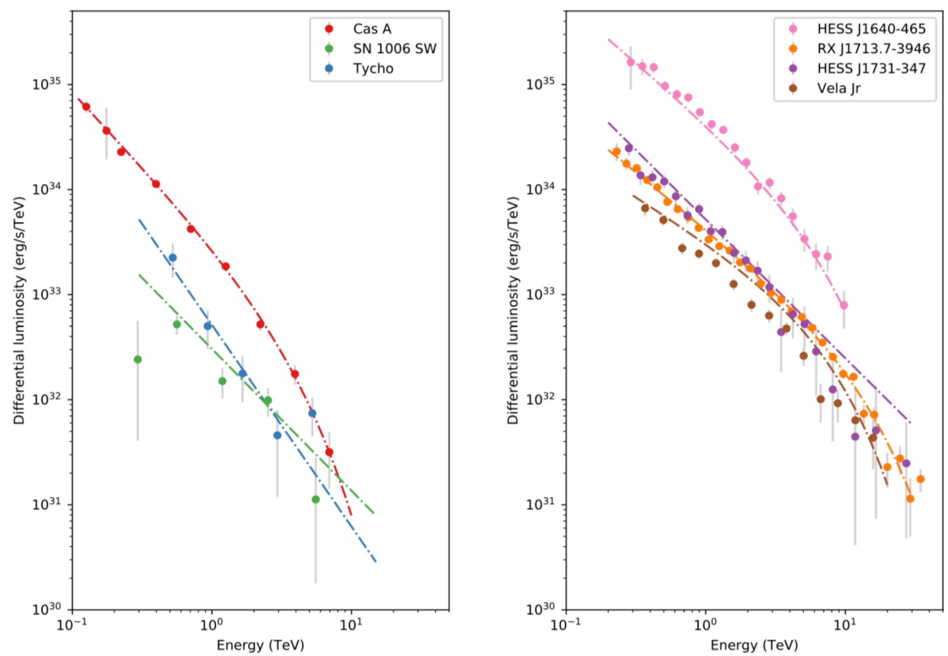
not perfect, but still acceptable, fits for spectral and spatial distributions of IC gamma-rays; suppressed thermal emission, comfortable p/e ratio (~10^2);small large-scale B-field (~ 10 μG)

both forward&reverse shock contribute to γ-rays

spectra of young SNRs above 1 TeV - steep with Γ= 2.3-2.6



TeV gamma-rays from from >10 young SNRs:
support to the SNR origin of galactic CRs,
but it is not yet clear whether SNRs alone can
provide the CR flux up to the *knee* (~1 PeV)



steep spectra or 'early' cutoffs ?

slope or intrinsic power-low index?

formally the spectra can be presented in the form:

$$dN/dE \propto E^{-\Gamma} \exp[-(E/E_0)^{\beta}]$$

with reasonable combination of E_0 and β, $\Gamma=2$ could be an option

price?

Eo < 10 TeV => Ep < 100 TeV is not a PeVatron

Eo > 10 TeV => Ep > 100 TeV and $\Gamma > 2.3$ can be a PeVatron

?

two options

- large power-law indices

  it is more realistic than Γ=2 of the "standard" DSA (M. Malkov, T. Bell, …)

  no constrains on the proton maximum energy from gamma-ray data:

  probing Emax ~ 1 PeV - very difficult

- "early cutoff"

  standard DSA but low-energy cutoff

  should we relax and accept that SNRs are main contributors to CRs but at TeV energies are overtaken by other source population ("PeVatrons") responsible for the knee region? (Laggage and Cesarsky 1983) ?

  or

  relate it to the much early "PeVatron Phase" - first 10 to 100 years after the SN explosion (Bell+, Zirakashvili+) and the escape of highest energy (>1 PeV) particles from the remnant energy particles

"large Γ or small Eo ?" - extension of observations to 100 TeV

searching for proton PeVatrons through their "echos":

multi-TeV radiation from dense clouds located outside the accelerator

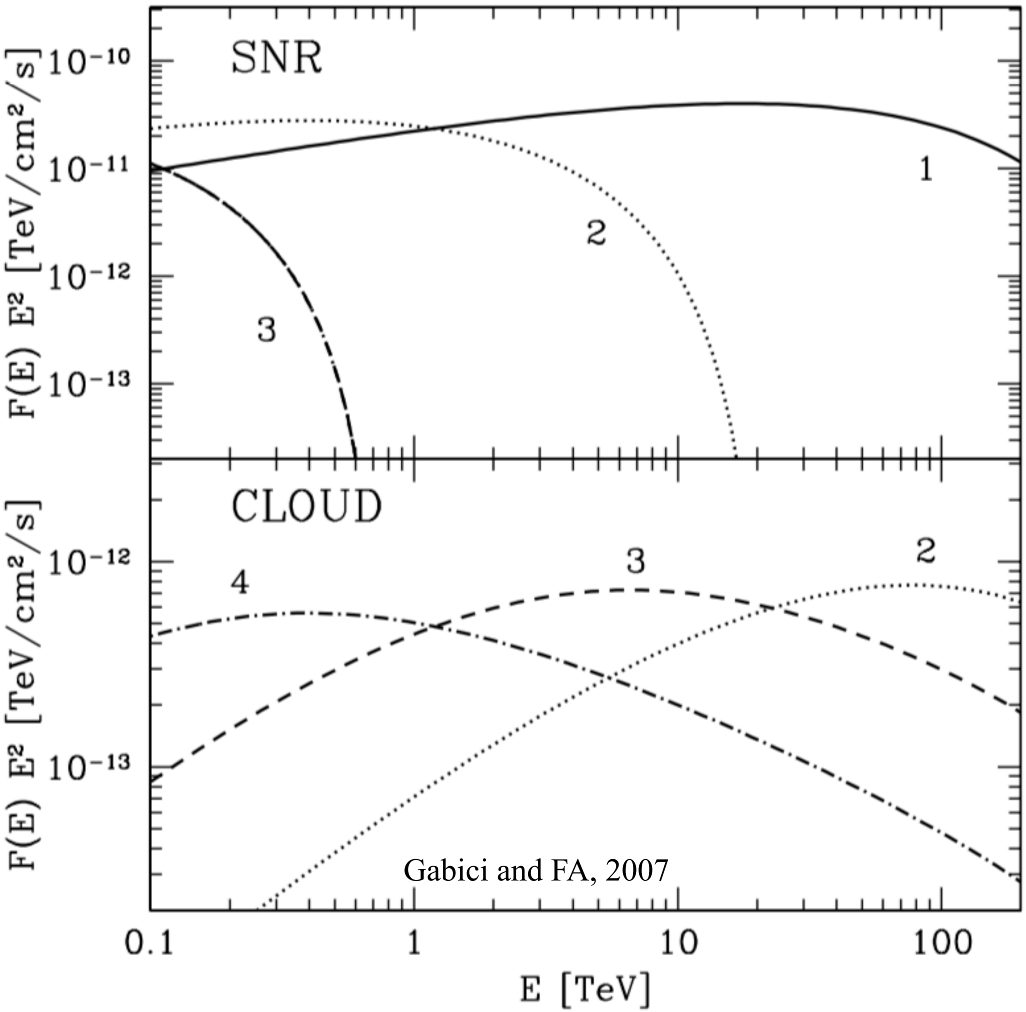
- protons of energy exceeding 100 TeV are accelerated and leave the shell at T<1000 yr or, more likely, <100 year, epochs

- γ-rays above 100 TeV expected only from very young SNRs - the chance of their detection is small

- if (by chance) a massive gas cloud appears in the 100 pc vicinity of SNR, "delayed" γ-rays signals arise when run-away partices reach the cloud

- detection of such delayed emission of multi-TeV γ-rays allows indirect but robust identification of the SNR as a proton PeVatron

gamma-rays from SNR and nearby molecular cloud



d=1 kpc

SNR:

$W=10^{51}$ erg

$n= 1\ cm^{-3}$

$f(p)\sim p^{-4}$

$p_{max}=5$ PeV

$p_{max}\sim t^{-2.4}$

Cloud:

R=100 pc

$M=10^4 Mo$

$D(E)=3x10^{29}(E/1PeV)^{0.5}\ cm^2/s$

1 - 400 yr; 2 - 2000 yr; 3 - 8000 yr; 4 - 32000 yr after the explosion

warning: don’t be tricked by propagation effects!

transition from rectilinear to diffusive regime of propagation

$$f(r,\mu) = \frac{Q}{4\pi c}\left(\frac{1}{r^2} + \frac{c}{rD}\right)\frac{1}{2\pi Z}\exp\left(-\frac{3D(1-\mu)}{rc}\right)$$

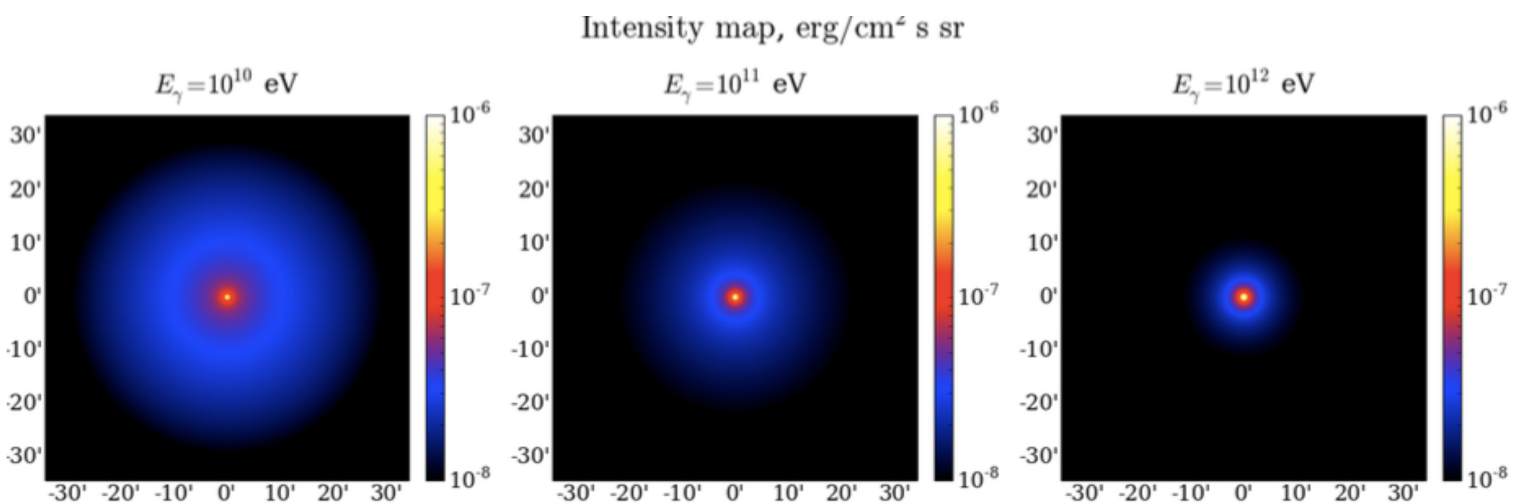
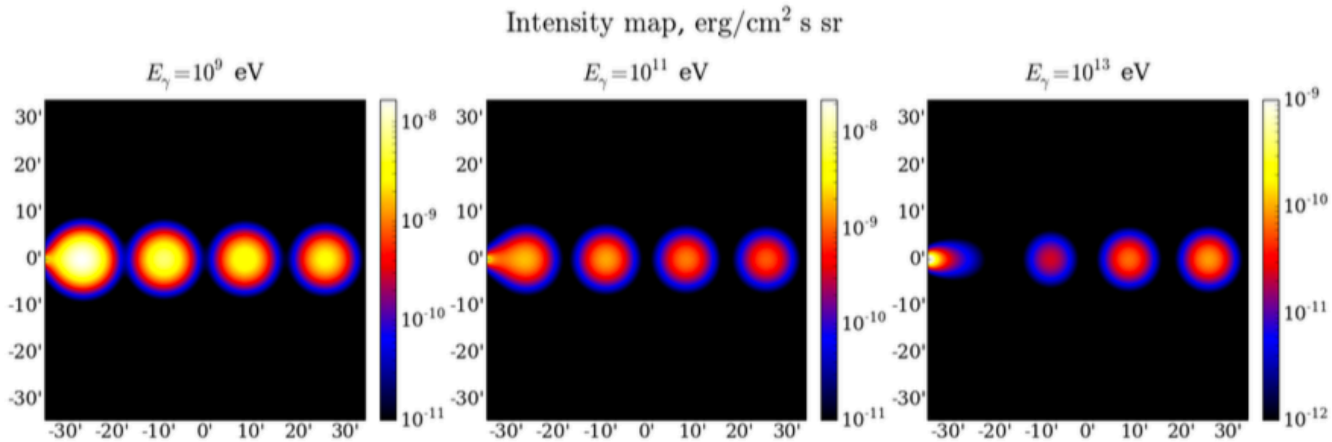


Figure 2: The intensity maps of gamma-ray emission at different energies. The spherical cloud with homogeneous density distribution is irradiated by the cosmic-ray source located in its centre. The gas density inside the accelerator is assumed very low, so the contribution of the accelerator to the gamma-ray emission is negligible. The maps are produced for the case of small diffusion coefficient (for details, see the text). For the distance to the source $d = 1$ kpc, the region of $\sim 1^\circ \times 1^\circ$ corresponds to the area $\sim 20 \times 20$ pc^2.

Prosekin, Kelner, FA 2015

warning:

transition from rectilinear to diffusive regime of propagation



d=1 kpc

intensity map of gamma-rays at different energies from a group of clouds located at different distances from the accelerator

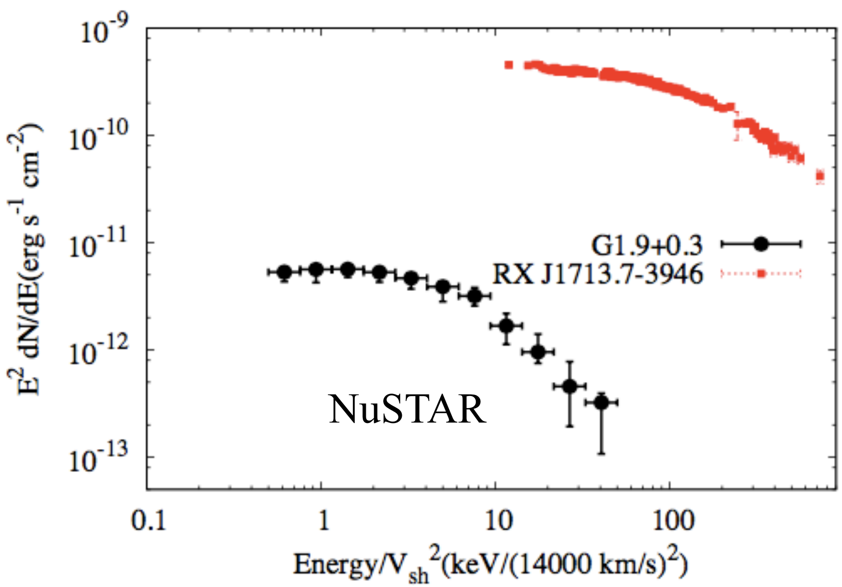
Prosekin, Kelner, FA 2015

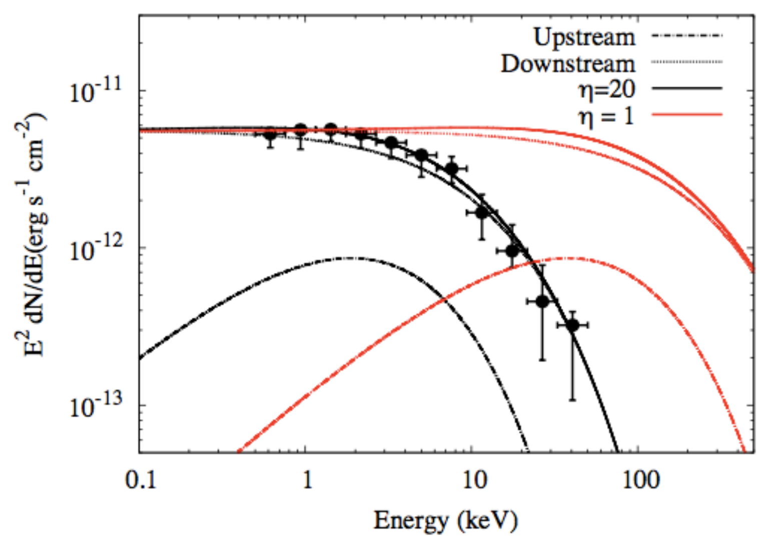
Very young SNRs as PeVatrons?

G1.9+0.3 - youngest (100yr-old) known SNR in Galaxy with the current shock speed v=14,000 km/s

$$h\nu_{\rm max} \approx 1(\mathrm{v_{sh}}/3000\ \mathrm{km/s})^2\ \mathrm{keV}$$

in the Bohm diffusion limit the peak should be around 20 keV but is detected at at 1 keV





Presently G1.9+0.3 does not operate as a PeVatron!

PeVatrons and Super-PeVatrons in Milky Way

do we expect acceleration of particles to PeV energies and well beyond?

stellar sources - very difficult but possible, in particular,

Supernova Remnants, Stellar Clusters/Superbubbles (extreme accelerators)

Pulsar Wind Nebulae electron PeVatron (absolute-extreme accelerators)

multi-PeV accelerators in our Galaxy?

extension of the cosmic ray spectrum well beyond 1 PeV =>
super-PeVatrons should exist in the Milky Way

SNRs, Supper-Bubbles, Pulsars ?

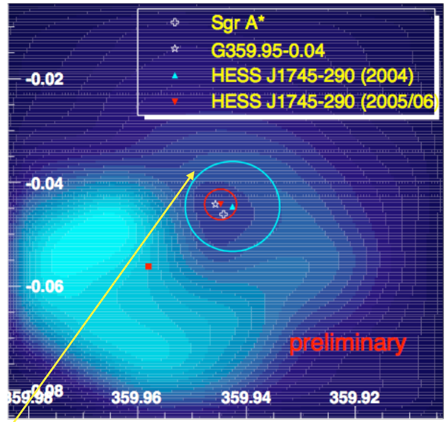
Galactic Wind halo?

Fermi Bubbles?

SMBH in the Galactic Center ?

PeVatron(s) in the Galactic Center!

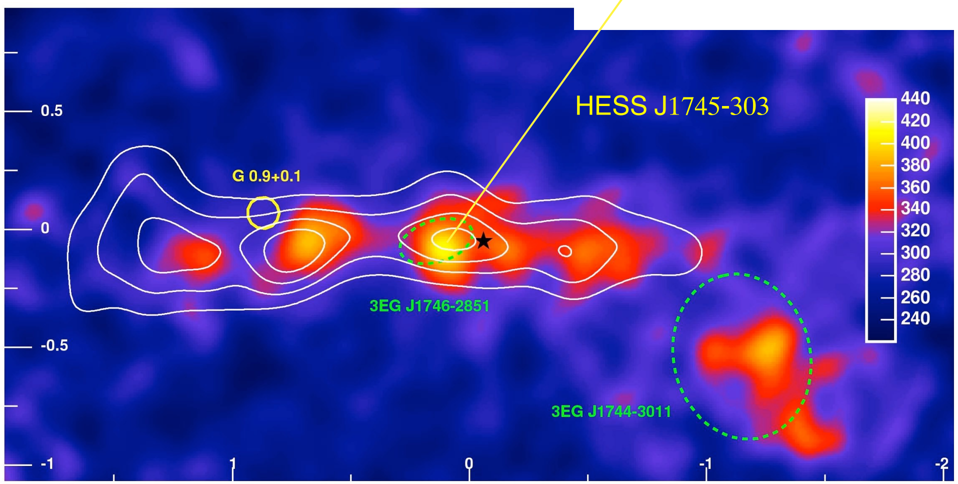
90 cm VLA radio image



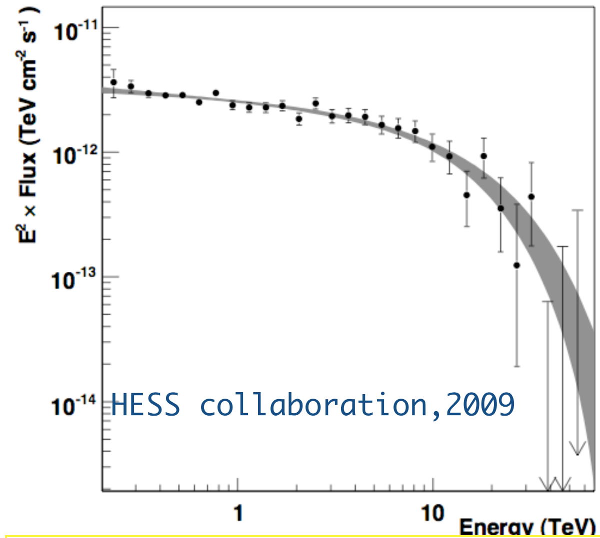
TeV gamma-rays
from Galactic Center

Sgr A* or the central diffuse < 10pc region or a plerion?

γ-ray emitting clouds



HESS collaboration,2006



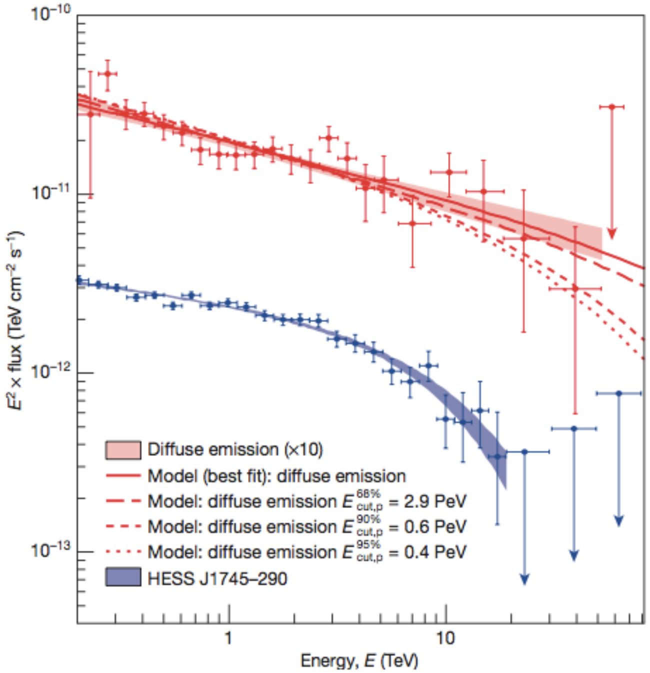
Energy spectrum:

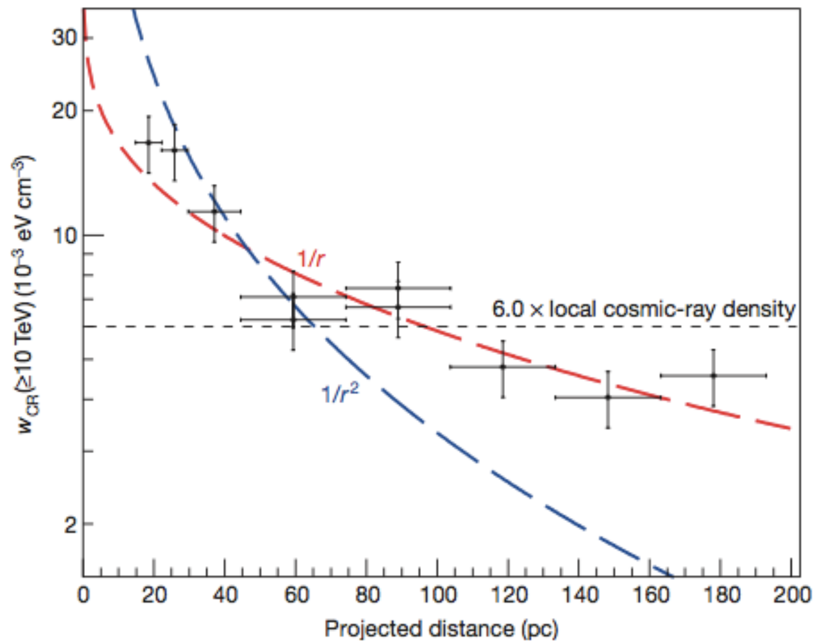
$$dN/dE = AE^{-\Gamma} \exp[(-E/E_{0)})^{\beta}]$$

$\beta=1$ $\Gamma=2.1$; $E_0=15.7$ TeV

$\beta=1/2$ $\Gamma=1.9$ E0=4.0 TeV

PeVatron located within R<10 pc and operating continuously over > 10^3 yr





no-cutoff in the gamma-ray spectrum up to **25 TeV**

=> *no-cutoff* in the proton spectrum up to ~ **1 PeV**

what do we expect?

1/r continuous source

$1/r^2$ wind or ballistic motion

constant burst like source

derived: **1/r** distribution

=> continuous acceleration !

implications?

- Galactic Center (GC) harbors a hadronic PeVatron within a few pc region around Sgr A* (a SMBH in GC)

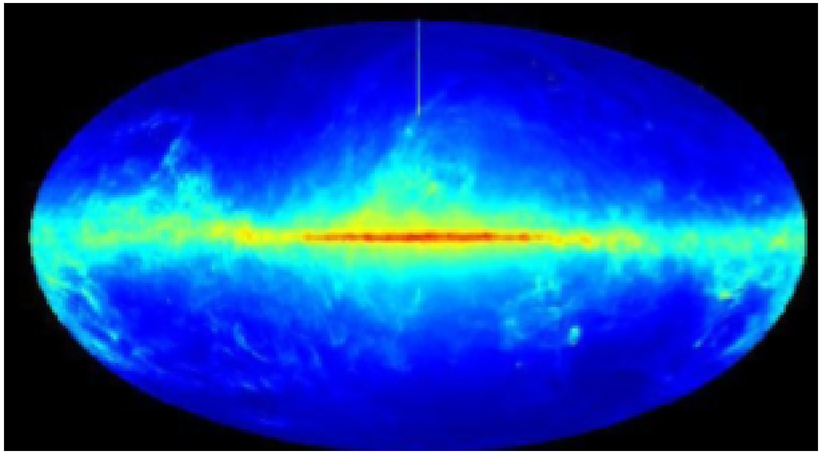
- 1/r type distribution of the CR density implies (quasi)continuous regime of operation of the accelerator with a power 10^{38} erg/s (on timescales 1 to 10 kyr) - a non negligible fraction of the current accretion power

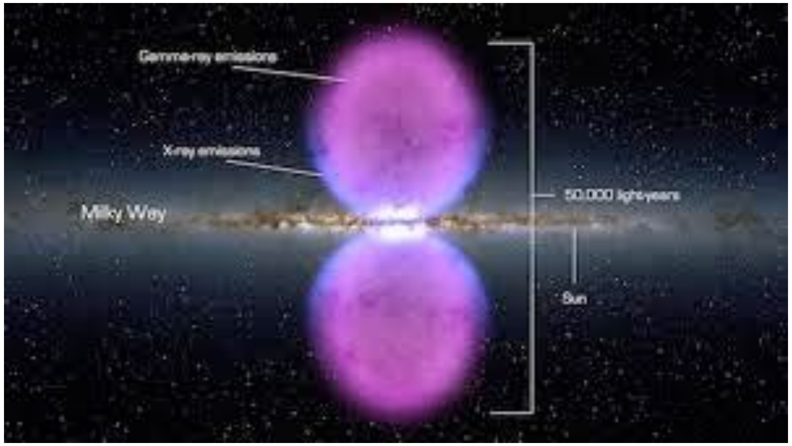
- this accelerator alone can account for most of the flux of Galactic CRs around the “knee” if its power over the last 10^6 years or so, has been maintained at average level of 10^{39} erg/s

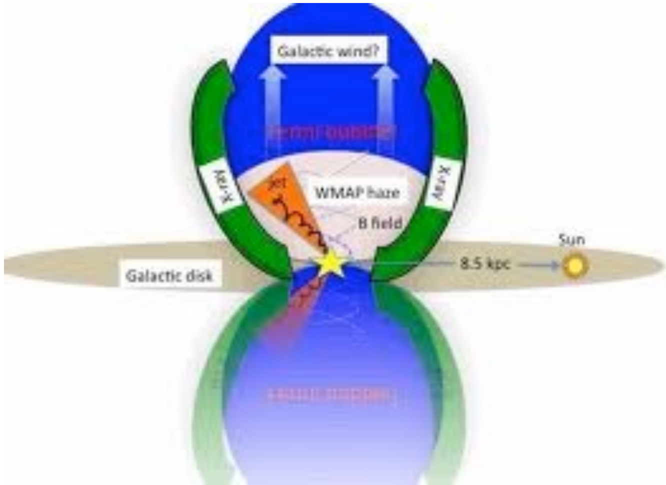
- escape of particles into the Galactic halo and their subsequent interactions with the surrounding gas, can be responsible for the sub-PeV neutrinos recently reported by the IceCube collaboration

SMBH or young massive-star clusters?

CRs from GC responsible for Fermi Bubbles?







and “IceCube Neutrinos” from a larger >>10 kpc halo ?

Young Massive Stars as Cosmic Ray PeVatrons?

Extended Regions surrounding Clusters of Young Massive Stars are sources sources of GeV, TeV and … PeV gamma-rays!

Westerlund 1, *Westerlund 2*, *30 Dor C* (in LMC)

CygnusOB2, *Westerlund 2*, *NGC3603*

Arches, *Quintuplet* and *Nuclear* ultracompact clusters in GC

- collective power in stellar wind 10^{38} - 10^{39} erg/s
- typical speeds of stellar winds several times 1000 km/s

continuous injections of CRs into ISM over (2-5) x 10^6 yrs formation of ~ 1/r radial distribution of CRs up to 200 pc; diffuse (typically irregular) gamma-ray morphology

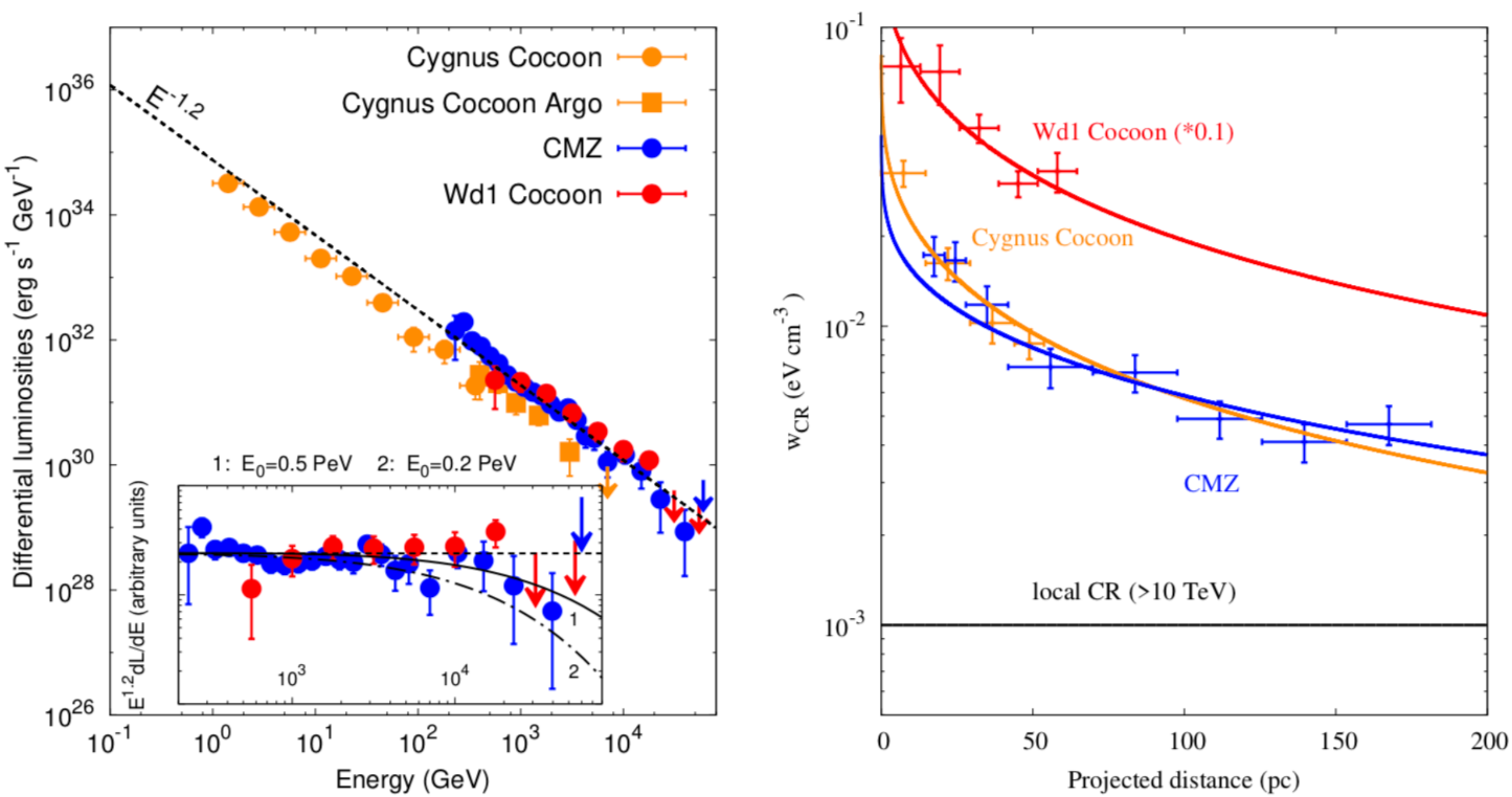


Figure 1: Gamma-ray luminosities and CR proton radial distributions in extended regions around the star clusters Cyg OB2 (Cygnus Cocoon) and Westerlund 1 (Wd 1 Cocoon), as well as in the Central Molecular Zone (CMZ) of the Galactic Centre assuming that CMZ is powered by CRs accelerated in *Arches*, *Quintuplet* and *Nuclear* clusters.

FA, Yang, Ona de Wilhelmi, 2018

Total energy in CRs within the size of radius Ro

$$W_{\rm p} = 4\pi \int_0^{R_0} w(r) r^2 \, {\rm d}r \approx 2.7 \times 10^{47} (w_0/1 \text{ eV}/\text{cm}^3)(\text{R}_0/10 \text{ pc})^2 \text{ erg}$$

Size of emission region - depends on D and To

$$R_{\rm D} = 2\sqrt{T_0 D(E)} \approx 3.6 \times 10^3 (D_{30} T_6)^{1/2} \text{ pc}$$

Efficiency of conversion of the wind kinetic energy to CRs

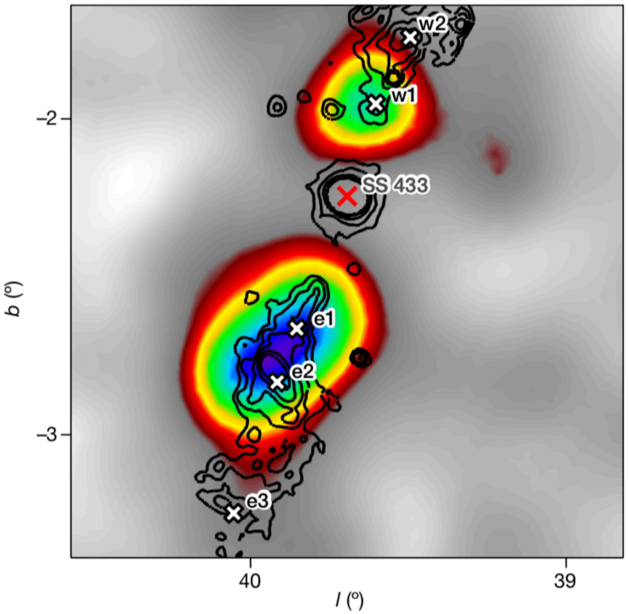
$$f(\geq 10 \text{ TeV}) \approx 1 w_0 D_{30} L_{39}^{-1}$$

For $E^{-2.3}$ proton spectrum, f(>10TeV) does not significantly exceed 1%
the diffusion coefficient D_{30} cannot be larger than 0.01; $R_D \sim 300$ pc

LHAASO, CTA - measurements of D and consequently f

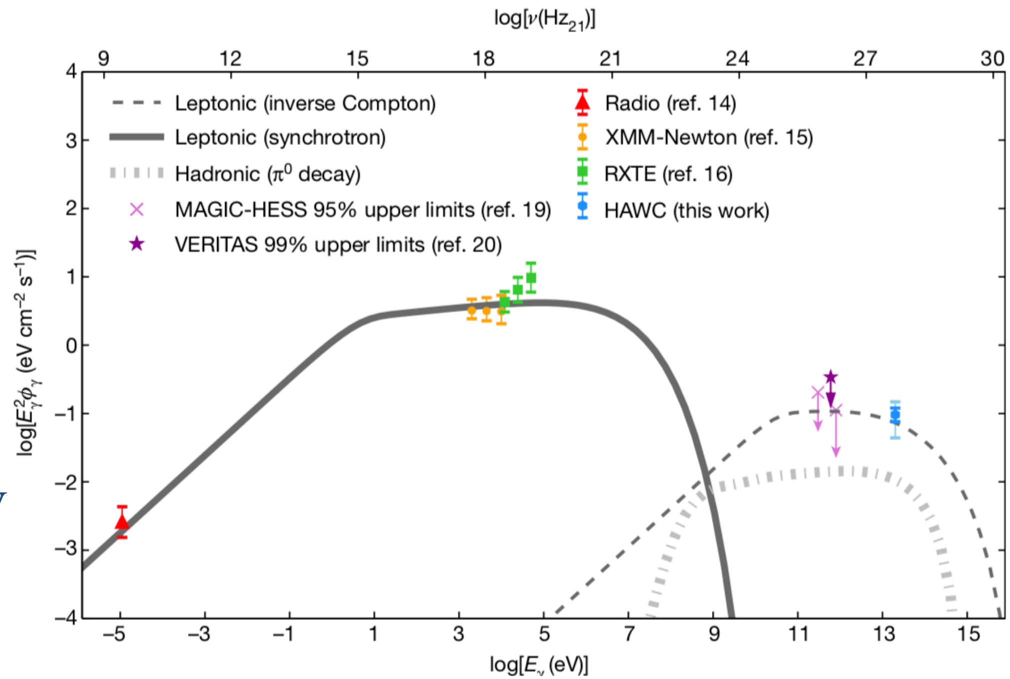
Other Pevatron candidates

detection of >10 TeV hard spectrum gamma-rays from SS 433



HAWC - HESS/MAGIC upper limits

spectrum as flat as E^{-2} extending 20 TeV



- E^{-2} electron spectrum with Eo=2 PeV
- gas density - not sufficient?

other Microquasars?

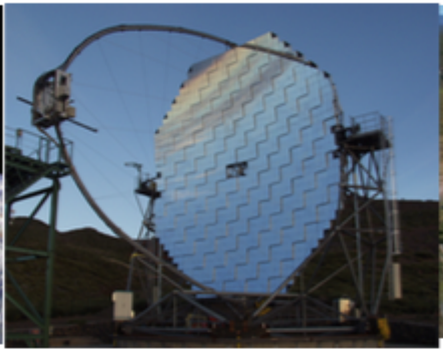
Cyg X-1, Cyg X-3, GRS 1915, … good candidates for acceleration of protons >>10^{15} eV

HE, VHE, and UHE Gamma-Ray Detectors

HE

VHE

UHE



future ?

(multi) GeV
energies
detection area
~10m^2
not realistic ?

1-100 MeV range
1m^2 is sufficient
PSF should be 1^o
realistic !

CTA - great
improvement

beyond CTA ?

1 GeV telescope?

10 to 100 km^2
multi-TeV array ?

CTA - great
on going

SGSO

new initiative

Next Generation Detectors

IACT arrays - high performance and great potential

- huge detection areas, potentially >> 1 km; photon statistics !
- good (~10 to 20%) energy resolution and
- good angular resolution (down to 1-2 arcmin)
- relatively large FoV (5 to 10 degree)

=> spectrometry, morphology, timing, surveys

- sensitivity for point-like sources down to 10^{-14} erg/cm^{2}s (impressive by standards of modern astronomical instruments!)

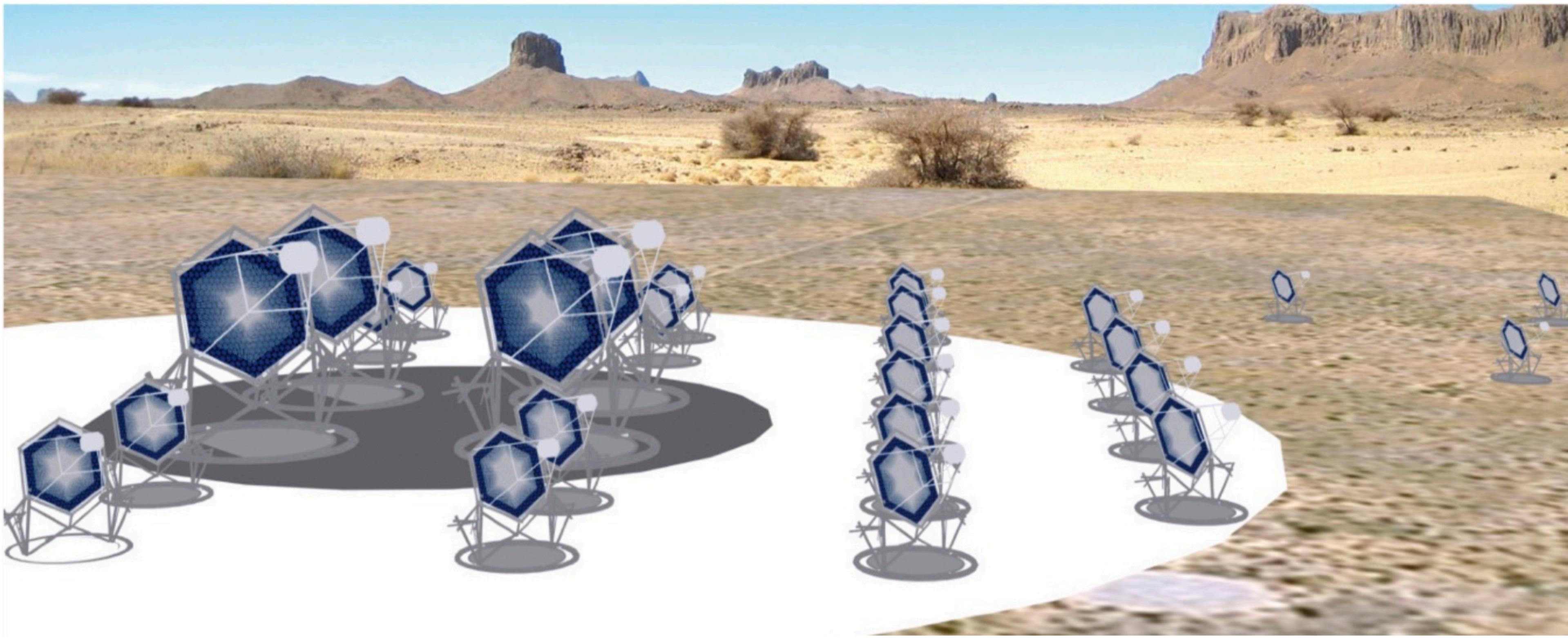
multi-functional tools:

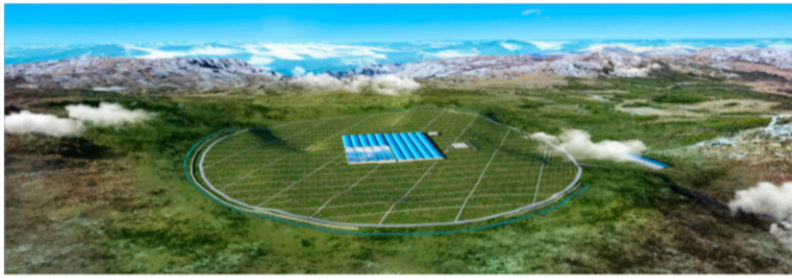
✓ extended sources: from SNRs to Clusters of Galaxies

✓ transient phenomena μQSOs, AGN, GRBs, ...

Galactic Astronomy | Extragalactic Astronomy | Observational Cosmology

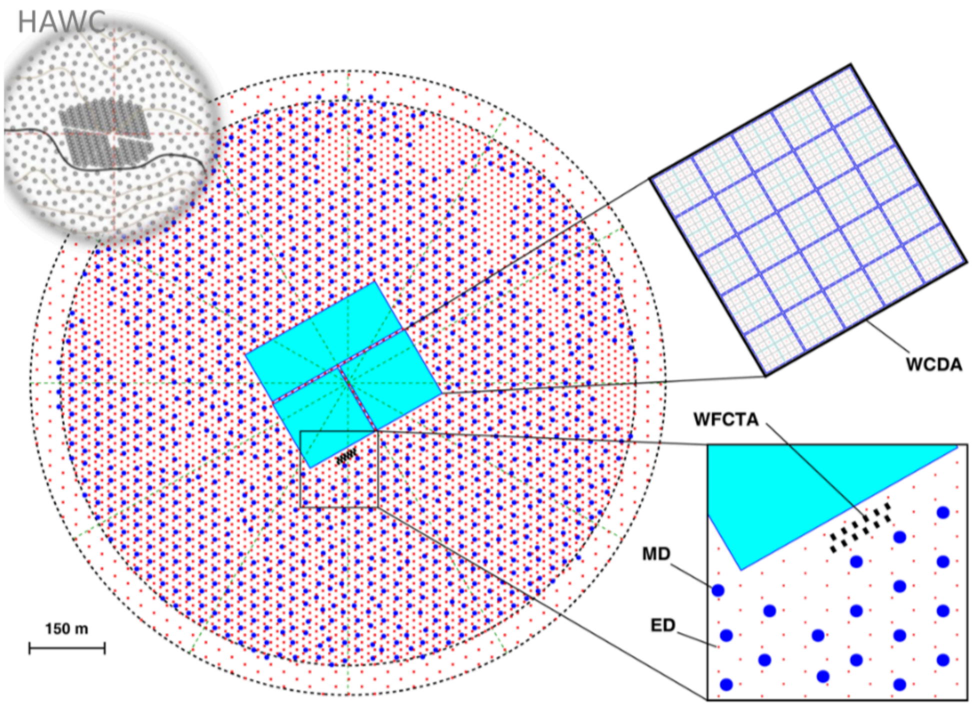
CTA - Cherenkov Telescope Array





LHAASO

Sichuan, China, 4410 m asl



5195 Scintillators
- 1 m^2 each
- 15 m spacing

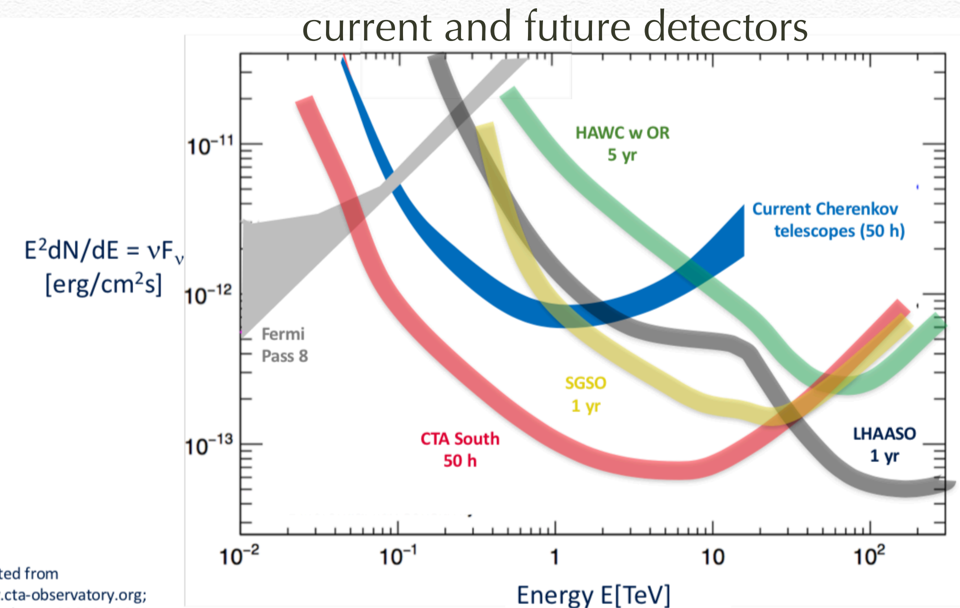
1171 Muon Detectors
- 36 m^2 each
- 30 m spacing

3000 Water Cherenkov Cells
- 25 m^2 each

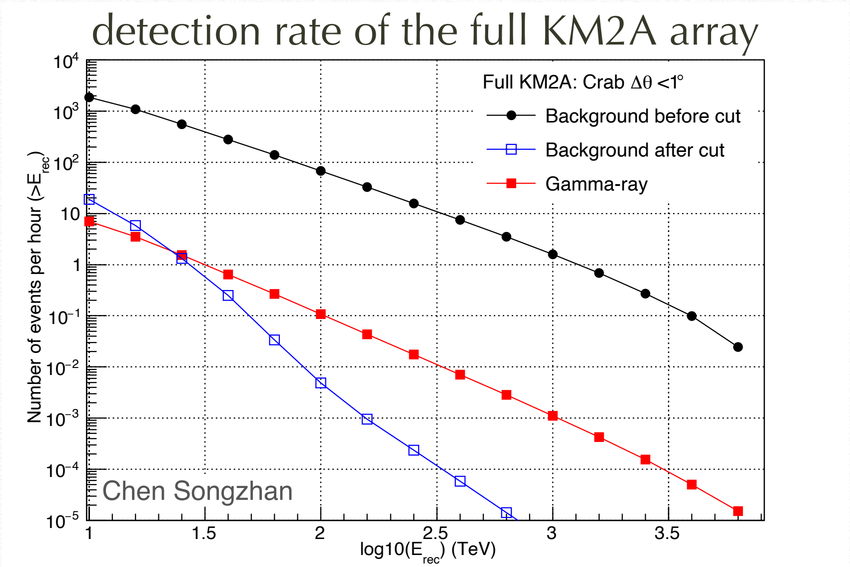
12 Wide Field Cherenkov Telescopes

First results of LHAASO - a kind of shock - many > 100 TeV sources!

LHAASO - a PeVatron hunter



adapted from www.cta-observatory.org; J. Goodman, COSPAR 2018; Z. Cao, La Palma 2018



KM2A - PSF: 25′ at 20 TeV, 12′ at 100 TeV
KM2A - energy resolution better than 20%

background-free detection of extended 1deg sources of >100 TeV gamma-rays of strength 0.1 Crab by KM2A with a rate 1 ph/100 h

ideal to study diffuse gamma-ray emission of the galactic disk, Fermi Bubbles

Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ-ray Galactic sources

Nature, June 3rd 2021

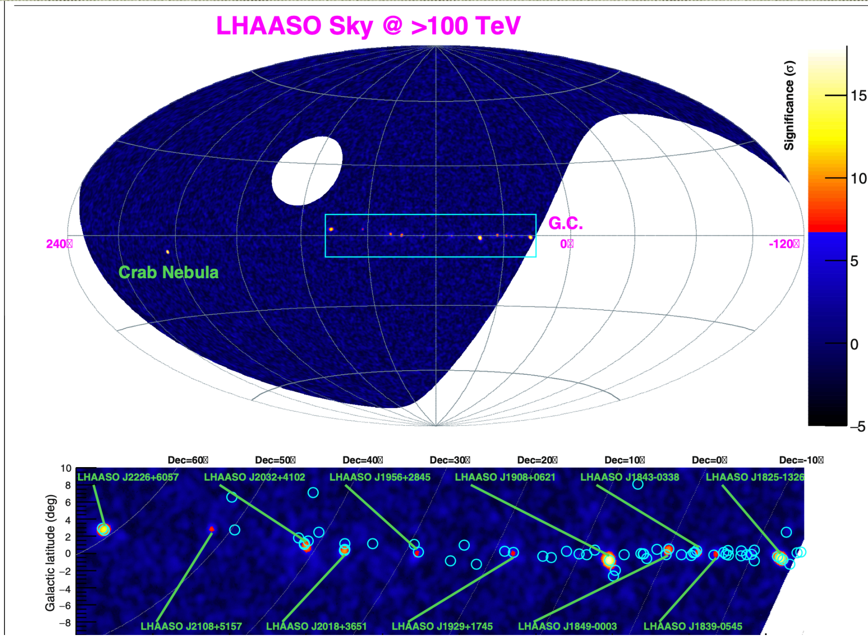
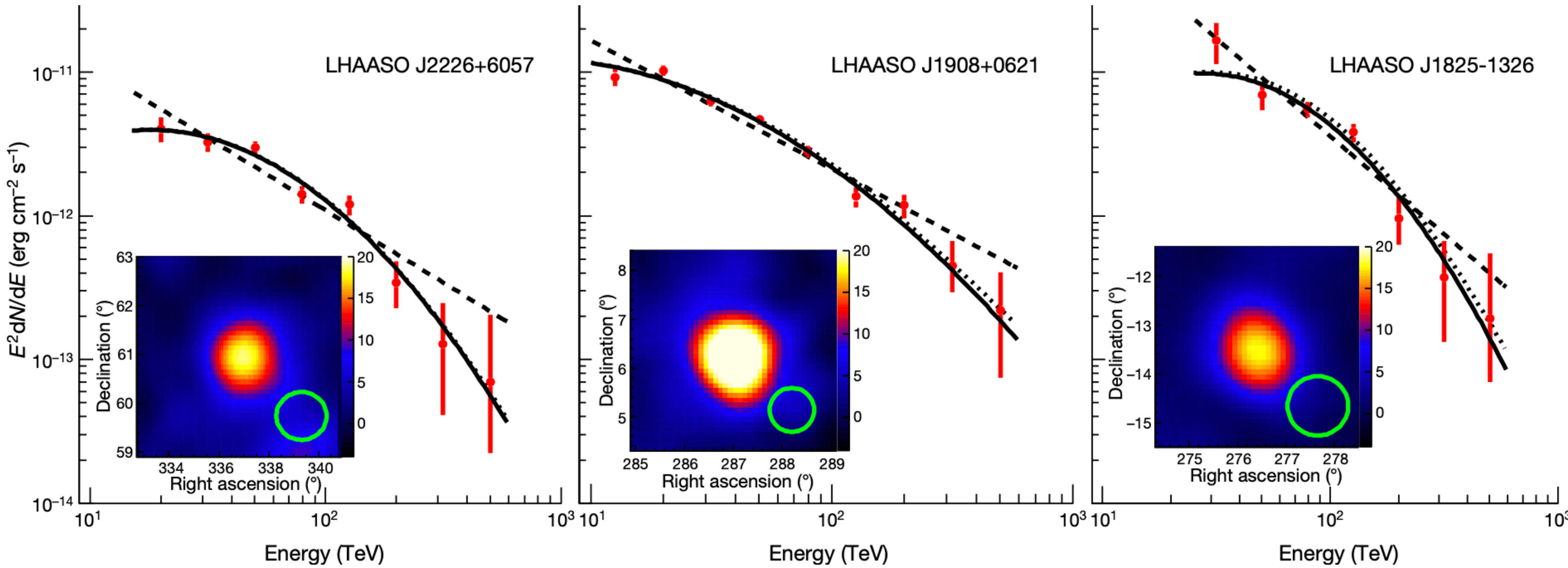


Table 1 | UHE γ-ray sources

Source name	RA (°)	dec. (°)	Significance above 100 TeV (×σ)	E_{max} (PeV)	Flux at 100 TeV (CU)
LHAASO J0534+2202	83.55	22.05	17.8	0.88 ± 0.11	1.00(0.14)
LHAASO J1825-1326	276.45	−13.45	16.4	0.42 ± 0.16	3.57(0.52)
LHAASO J1839-0545	279.95	−5.75	7.7	0.21 ± 0.05	0.70(0.18)
LHAASO J1843-0338	280.75	−3.65	8.5	$0.26\,_{-0.10}^{+0.16}$	0.73(0.17)
LHAASO J1849-0003	282.35	−0.05	10.4	0.35 ± 0.07	0.74(0.15)
LHAASO J1908+0621	287.05	6.35	17.2	0.44 ± 0.05	1.36(0.18)
LHAASO J1929+1745	292.25	17.75	7.4	$0.71\,_{-0.07}^{+0.16}$	0.38(0.09)
LHAASO J1956+2845	299.05	28.75	7.4	0.42 ± 0.03	0.41(0.09)
LHAASO J2018+3651	304.75	36.85	10.4	0.27 ± 0.02	0.50(0.10)
LHAASO J2032+4102	308.05	41.05	10.5	1.42 ± 0.13	0.54(0.10)
LHAASO J2108+5157	317.15	51.95	8.3	0.43 ± 0.05	0.38(0.09)
LHAASO J2226+6057	336.75	60.95	13.6	0.57 ± 0.19	1.05(0.16)

Celestial coordinates (RA, dec.); statistical significance of detection above 100 TeV (calculated using a point-like template for the Crab Nebula and LHAASO J2108+5157 and 0.3° extension templates for the other sources); the corresponding differential photon fluxes at 100 TeV; and detected highest photon energies. Errors are estimated as the boundary values of the area that contains ±34.14% of events with respect to the most probable value of the event distribution. In most cases, the distribution is a Gaussian and the error is 1σ.



Extended Data Table 1 | Number of on-source events of energy >100 TeV, residual CR background events and corresponding exposure time for the 12 UHE sources

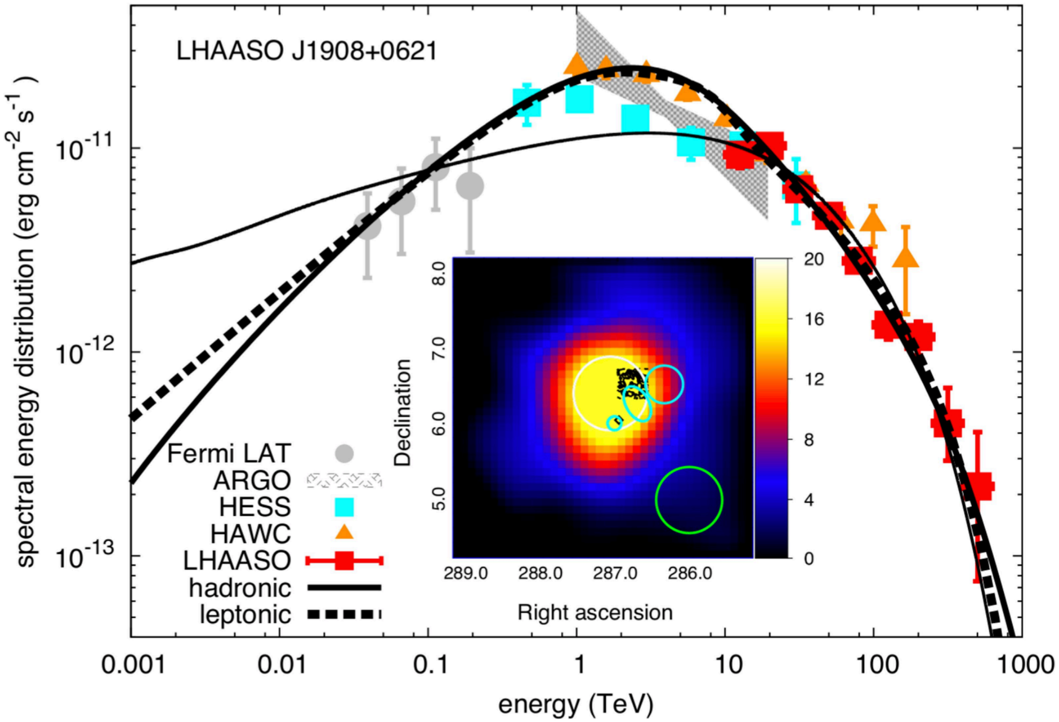
source	Number of on-source events	number of background events	exposure (hr)
LHAASO J0534+2202	67	5.5	2236.4
LHAASO J1825-1326	61	3.2	1149.3
LHAASO J1839-0545	26	4.2	1614.5
LHAASO J1843-0338	30	4.3	1715.4
LHAASO J1849-0003	36	4.8	1865.3
LHAASO J1908+0621	74	5.1	2058.0
LHAASO J1929+1745	29	5.8	2282.6
LHAASO J1956+2845	34	6.1	2461.5
LHAASO J2018+3651	42	6.3	2610.7
LHAASO J2032+4102	45	6.7	2648.2
LHAASO J2108+5157	30	6.4	2525.8
LHAASO J2226+6057	60	6.2	2401.3

Extended Data Table 2 | List of energetic astrophysical objects possibly associated with each LHAASO source

LHAASO Source	Possible Origin	Type	Distance (kpc)	Age (kyr)[a]	L_s (erg/s)[b]	Potential TeV Counterpart[c]
LHAASO J0534+2202	PSR J0534+2200	PSR	2.0	1.26	4.5×10^{38}	Crab, Crab Nebula
LHAASO J1825-1326	PSR J1826-1334	PSR	3.1 ± 0.2^d	21.4	2.8×10^{36}	HESS J1825-137, HESS J1826-130,
	PSR J1826-1256	PSR	1.6	14.4	3.6×10^{36}	2HWC J1825-134
LHAASO J1839-0545	PSR J1837-0604	PSR	4.8	33.8	2.0×10^{36}	2HWC J1837-065, HESS J1837-069,
	PSR J1838-0537	PSR	1.3^e	4.9	6.0×10^{36}	HESS J1841-055
LHAASO J1843-0338	SNR G28.6-0.1	SNR	9.6 ± 0.3^f	$< 2^f$	—	HESS J1843-033, HESS J1844-030, 2HWC J1844-032
LHAASO J1849-0003	PSR J1849-0001	PSR	7^g	43.1	9.8×10^{36}	HESS J1849-000, 2HWC J1849+001
	W43	YMC	5.5^h	—	—	
LHAASO J1908+0621	SNR G40.5-0.5	SNR	3.4^i	$\sim 10 - 20^j$	—	MGRO J1908+06, HESS J1908+063,
	PSR 1907+0602	PSR	2.4	19.5	2.8×10^{36}	ARGO J1907+0627, VER J1907+062,
	PSR 1907+0631	PSR	3.4	11.3	5.3×10^{35}	2HWC 1908+063
LHAASO J1929+1745	PSR J1928+1746	PSR	4.6	82.6	1.6×10^{36}	2HWC J1928+177, 2HWC J1930+188,
	PSR J1930+1852	PSR	6.2	2.9	1.2×10^{37}	HESS J1930+188, VER J1930+188
	SNR G54.1+0.3	SNR	$6.3^{+0.8\ d}_{-0.7}$	$1.8 - 3.3^k$	—	
LHAASO J1956+2845	PSR J1958+2846	PSR	2.0	21.7	3.4×10^{35}	2HWC J1955+285
	SNR G66.0-0.0	SNR	2.3 ± 0.2^d	—	—	
LHAASO J2018+3651	PSR J2021+3651	PSR	$1.8^{+1.7\ l}_{-1.4}$	17.2	3.4×10^{36}	MGRO J2019+37, VER J2019+368,
	Sh 2-104	H II/YMC	$3.3 \pm 0.3^m/4.0 \pm 0.5^n$	—	—	VER J2016+371
LHAASO J2032+4102	Cygnus OB2	YMC	1.40 ± 0.08^o	—	—	TeV J2032+4130, ARGO J2031+4157,
	PSR 2032+4127	PSR	1.40 ± 0.08^o	201	1.5×10^{35}	MGRO J2031+41, 2HWC J2031+415,
	SNR G79.8+1.2	SNR candidate	—	—	—	VER J2032+414
LHAASO J2108+5157	—	—	—	—	—	—
LHAASO J2226+6057	SNR G106.3+2.7	SNR	0.8^p	$\sim 10^p$	—	VER J2227+608, Boomerang Nebula
	PSR J2229+6114	PSR	0.8^p	$\sim 10^p$	2.2×10^{37}	

- firmly identified - Crab (Nebula);
- no yang SNRs (Cas A, Tycho,…)
- middle-age SNRs ?
- PWNe and/or PHs
- Stellar clusters - W43, Cygnus Cocoon surrounding Cygnus OB
- - - - - -

an example of a PeVatron



PH around PSR J1907+0602

or

SNR G40.5-0.5 + GMC

or

something else

- - - IC electron spectrum: $dN/dE \propto E^{-1.75}\exp[-(E/800\mathrm{TeV})^2]$

6% of the spin-down luminosity of PSR J1907+0602. (2.4 kpc)

____ pp proton spectrum: $dN/dE \propto E^{-1.85}\exp[-(E/380\mathrm{TeV})]$

____ pp proton spectrum: $dN/dE \propto E^{-1.2}$ $E \leq 25\mathrm{TeV}$;

$\propto E^{-2.7}\exp[-(E/1.3\mathrm{PeV})]$ $E \geq 25\mathrm{TeV}$

Summary:

Extreme accelerators - perfectly designed machines accelerating particles at a rate on the edge of reality

but these accelerators do exist

to understand the nature of these objects is a great challenge and excitement

knowledges of many disciplines is needed

- EM, MHD, Plasma Physics - acceleration
- QEM, High Energy Physics - radiation signatures

we have adequate tools - IACT arrays and LHAASO; Fermi, NuStar, eRosita…

CDY has resources to contribute substantially to these studies